Balance and response time in patients with chronic tennis elbow

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Abstract

Background: Tennis elbow is a common condition that is easy to diagnose however, the optimal approach to management is still an area of considerable debate with limited evidence to support current practice. This is due to the ambiguous nature of its aetiology and pathology, which remain poorly understood. Bilateral sensorimotor deficits in the upper limb have been found in patients with unilateral tennis elbow, as they had slower response time and slower speed of movement. Research suggests that these patients could also have generalised sensorimotor deficits due to peripheral and central sensitisation. However, only bilateral sensorimotor deficits have been investigated suggesting that research is warranted to investigate the generalised sensorimotor deficits in patients with chronic tennis elbow. Therefore, it is the intention of this research to provide new knowledge in the area of sensorimotor function in these patients.

Methods: This PhD programme consisted of two phases, the first phase involved healthy participants (n=22) and the second phase involved patients with chronic tennis elbow (n=11). This study was quasi experimental and investigated sensorimotor function by measuring balance and response time of the upper and lower limbs. The outcome measure for balance was time to boundary (TtB) in the anterio-posterior (ap) and medio-lateral (ml) directions. For the response time, the outcome measures were 1-choice response time and 2-choice response time. The test-retest reliability was assessed for these outcome measures using the intraclass correlation coefficient (ICC) and the standard error of measurement and yielded good to excellent reliability estimates.

Results: Following descriptive analysis and tests for normality and homogeneity of variance, the data was analysed using a mixed design ANOVA. Results showed that patients with chronic tennis elbow have more balance instability when compared to healthy participants as they were closer to reach their stability boundary in the anterio-posterior direction.

Conclusion: The findings of this research add new knowledge to the field of sensorimotor function in patients with chronic tennis elbow and enhance the understanding of this condition between health professionals.

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Abbreviations

ACL	Anterior cruciate ligament
ANOVA	Analysis of variance
Ap	Anterio-posterior
BOS	Base of support
COG	Centre of gravity
COM	Centre of mass
COP	Centre of pressure
ECRB	Extensor carpi radialis brevis
ECRL	Extensor carpi radialis longus
ECU	Extensor carpi ulnaris
EDC	Extensor digitorum communis
EMG	Electromyography
MRI	Magnetic resonance imaging
IASP	International association for the study of pain
ICC	Intraclass correlation coefficient
K-S	Kolmogorov-Smirnov test of normality
ml	Mediolateral
NHS	National health service
RCT	Randomised controlled trial
RMS	Root mean square
RT	Response time
TE	Total excursion
TtB	Time to boundary
TtBr	Time to boundary (Riccio method)
TtBs	Time to boundary (Slobounov method)
TtC	Time to contact
SM	Speed of movement
VTtC	Virtual time to contact

Introduction

The economic burden of chronic tennis elbow should not be underestimated as it commonly affects adults aged between 30 and 50 years old (NHS 2010). Given that it is more prevalent in the working population, the impact on the economy due to absence from work is great (Hong *et al.* 2004). The cost of physiotherapy to the NHS in the current financial crisis is also significant as conservative management is the first option of treatment for people with tennis elbow. Furthermore, the high recurrence rate of tennis elbow adds to the burden of the condition as patients are expected to seek medical care. The chronicity of tennis elbow is challenging and the conservative treatment fail to relieve the symptoms in these patients. Moreover, there is no consensus on the best approach of conservative treatment as research findings are contradictory in this regard. Therefore, in order to have an effective management of chronic tennis elbow a better understanding of the condition is required.

This PhD programme was a clinically driven study in response to an observation by experts in shoulder and elbow management at the Host organisation[1] who noticed over a period of time that patients with chronic tennis elbow appeared to have poor balance when assessed. On reviewing the literature it is apparent that there are no studies investigating balance in patients with chronic tennis elbow. However, a few studies have investigated the sensorimotor function of the upper limb in these patients and found that bilateral sensorimotor deficits were present in patients with unilateral chronic tennis elbow. It has been suggested that these patients could also have generalised sensorimotor deficits due to peripheral and central sensitisation. Nevertheless, generalised sensorimotor deficits have not been investigated in chronic tennis elbow and research in this field is warranted. This study is the first study to investigate balance and response time of the lower limb in patients with chronic tennis elbow. This study has also investigated response time in the upper limb replicating the studies of Pienimakie *et al.* (1997), Bisset *et al.* (2006) and Bisset *et al.* (2009). The

1 The Host organisation is one of the UK's largest acute teaching hospitals and provides specialist local and regional services and is the home for the largest orthopaedic surgery in the country. http://www.drfosterhealth.co.uk/hospital-guide/hospital/nhs/Northern-General-Hospital-503.aspx

purpose of this research is to enhance the understanding of the sensorimotor function in patients with chronic tennis elbow by investigating balance and response time in the upper and lower limbs.

Health professionals who are involved in the management of tennis elbow have always viewed tennis elbow as a local tendon pathology. Furthermore, the aetiology and pathology of tennis elbow is still not clearly understood, therefore, the management is based on treating the symptoms of pain and muscle weakness. Despite the findings of sensorimotor deficits in patients with chronic tennis elbow, the current management of tennis elbow is not addressing the sensorimotor involvement. Health professionals have been providing the same treatment for tennis elbow for decades. It is clear that the new knowledge provided by studies on sensorimotor deficits is not being translated into clinical practice violating the concept of evidence based practice. Therefore, this research seeks to address this gap between scientific evidence and clinical practice by providing health professionals with new knowledge about the sensorimotor function in patients with chronic tennis elbow.

The theoretical framework for this thesis was established following the "new integrative model of tennis elbow" proposed by Coombes *et al.* (2009). This model hypothesises that three factors contribute to the development of tennis elbow; tendon pathology, sensorimotor and proprioceptive changes and pain system changes. This research aims to contribute to the second element of this model by investigating balance and response time in patients with chronic tennis elbow.

In regard to the response time measurement in this study, the protocol used by Pienimakie *et al.* (1997), Bisset *et al.* (2006) and Bisset *et al.* (2009) has been followed. These studies used the term reaction time instead of response time. However, the term response time is more appropriate to be used as the term reaction time is commonly used in studies that involve electromyography (EMG) which has not been used in these studies. Therefore, the term response time will be used throughout this thesis, a detailed justification is presented under section 1.3.1.

This work is novel and original as it is the first study to investigate balance and response time of lower limb in patients with chronic tennis elbow while previous research have only investigated response time of the upper limb in these patients. It challenges current management of tennis elbow which solely views the condition as

tendon pathology and aims to treat pain and muscle weakness. It recognises the importance of bridging the gap between research and clinical practice in order to provide an evidence based care as health professionals are not integrating sensorimotor deficits in the management of chronic tennis elbow.

This thesis comprises five chapters. Chapter 1 is a critical review of the literature relevant to this research programme. Chapter 2 describes the methods used in this study. Chapter 3 examines the test- retest reliability of the outcome measures used in this study (time to boundary and response time). Chapter 4 presents the data analysis and results. Finally, chapter 5 includes a discussion of the research findings, the limitations of the study, implications for future research and conclusion.

Chapter 1

Literature Review

Chapter 1: Literature Review

The literature review chapter is divided into three main sections: tennis elbow, balance and postural control and response time. The first section will review the ambiguous picture of the aetiology, pathology and therapeutic approaches for tennis elbow and why it is an area of interest. The second and third sections will review the outcome measures used in this study, their relevance and why they were selected to be measured in patients with tennis elbow.

1.1 Tennis elbow

1.1.1 Introduction

Tennis elbow, also known as lateral epicondylitis or lateral epincondylalgia is a common disorder of the arm. In the UK it affects about five in a thousand each year and it occurs mainly in adults aged between 30 and 50 years old (NHS 2010). Prevalence studies have reported a prevalence rate of 1.3% in the general population (Walker-Bone *et al.* 2004; Shiri *et al.* 2006). There is no incidence difference between males and females (Hamilton 1986). Patients with tennis elbow complain of pain at the dorsal aspect of the arm that is aggravated by palpation and active or resisted wrist extension, the pain radiates into the dorsal aspect of the forearm and hand (Slater *et al.* 2003; Slater *et al.* 2005). Other symptoms include reduced grip strength and impaired arm function due to the weakness of wrist extensors (Pienimaki *et al.* 1997). In addition to the previously described clinical symptoms bilateral sensorimotor impairments are also present in tennis elbow; these include slower response time and decreased speed of movement (Pienimaki *et al.* 1997; Bisset *et al.* 2006; Bisset *et al.* 2009). Moreover, elbow proprioception was found to be poorer in patients with unilateral and bilateral tennis elbow when compared to a control group (Juul-Kristensen *et al.* 2008).

Tennis elbow is sometimes classified as a self limiting disease as symptoms will subside on their own with physiotherapy treatment or with adequate rest and time (Hong *et al.* 2004). However, there is a group of patients, estimated at around 5% to 10% who

will develop chronic and recurrent tennis elbow that is resistive to treatment and will require surgical interference (Boyd *et al.* 1973; Coonrad and Hooper 1973). The chronicity of tennis elbow is challenging, and the failure of conservative treatment is frustrating for patients, carers and health professionals. Tennis elbow is also claimed to be an economic burden because of the absence of work in the working population where it is most prevalent (Hong *et al.* 2004). Therefore, effective and accurate management of tennis elbow is warranted. In order to have an effective management a better understanding of the condition is required.

The pathology of tennis elbow has always been described as having a purely musculoskeletal origin, yet the sensorimotor deficits suggest a neurological involvement. Moreover, when neural tension tests were applied on patients with tennis elbow; the neural tissue of their arms was significantly less extensible; which also indicates a neural tissue involvement in these patients (Yaxley and Jull 1993). In order to encompass the challenging aspects of the unclear aetiology, recurrence and resistance to treatment in some patients with tennis elbow, a new integrative model for tennis elbow had been proposed by Coombes *et al.* (2009). Their model conceptualises tennis elbow as the result of a multi-factorial pathology that involves tendon pathology, pain system changes and motor system impairments. This model will be discussed in more detail later in this section.

1.1.2 Aetiology

Although the clinical picture of tennis elbow is clear and well known to health professionals and patients, the aetiology and pathogenesis are still not completely understood and remain unclear (Slater *et al.* 2003; Slater *et al.* 2005; Coombes *et al.* 2009 and Zeisig *et al.* 2009). It is claimed that tennis elbow is idiopathic or a work related condition (Boyer and Hastings 1999). People who work in occupations that involve repetitive hand intensive work are at higher risk of developing tennis elbow (Chiang *et al.* 1993). Although it is called tennis elbow, less than 5%- 10% of patients diagnosed with tennis elbow are actually tennis players (Boyer and Hastings 1999). However, this name is the most popular among patients and health professionals therefore, it will be used in this thesis, despite the fact that the name "lateral

epicondylalgia" might be more representative of the condition without any indication of the aetiology because the suffix "algia" means pain (Fedorczyk 2006). There are different theories of aetiologies for tennis elbow; but they are all tissue based pathologies (Kibler 1995). The most popular theory was the inflammation of the origin of the extensor Carpi radialis hence the name epicondylitis; however, different studies failed to detect inflammatory cells indicating a non inflammatory process (Alfredson *et al.* 2000). Other theories that are evolving rapidly and seem more appropriate are the overuse or biomechanical model that focuses on repetitive loading that will lead to degenerative changes in the tendon of extensor carpi radialis or dysfunctional and immature healing (Skinner and Curwin 2007).

A multifactorial model of causation in athletic injuries was proposed by Meeuwisse (1994) (Figure 1). This model was applied to different athletic injuries including tennis elbow. Although the model is used in athletes, it could be applied generally to individuals who are involved in repetitive or over loading activities. The model suggests that intrinsic risk factors like age, flexibility, strength and previous injury create a predisposed individual. The interaction with extrinsic risk factors (which could be the biomechanics, demands, intensity and frequency of a specific motion) will produce a susceptible individual and finally an inciting event will lead to the production of clinical symptoms. An inciting event is not necessarily an isolated incident, it could be the accumulation of intense exposure or more exposure to the extrinsic factors.

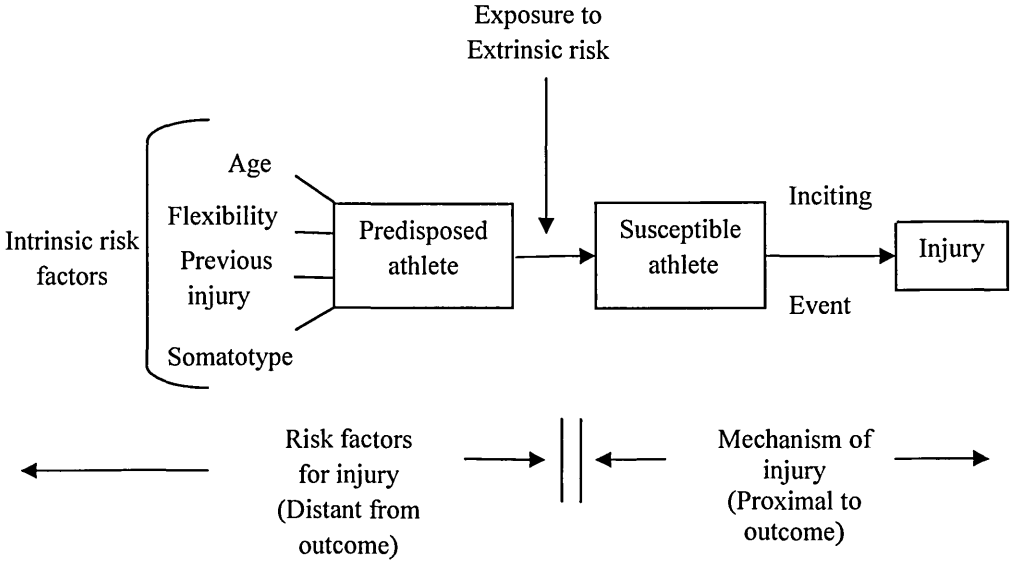

Figure 1: Multifactorial model for injury causation (Redrawn from Meeuwisse 1994).

1.1.3 Pathology

Like the aetiology, the pathogenesis process of tennis elbow is still ambiguous. Although a number of pathologies have been described in the literature, each one lacks the ability to explain all the characteristics of tennis elbow which reflect the possibility of a multifactorial pathology (Coombes *et al.* 2009). The majority of the authors changed the term lateral epicondylitis in favour of other broader terms like lateral epicondylalgia or lateral elbow tendinopathy, which reflects the non-inflammatory process of the condition and perhaps indicates that the aetiology is not yet clearly understood. However, the term tennis elbow remains the most commonly used name for patients, carers and even health professionals. Histopathological, radiological and sonographic findings indicate that tennis elbow involves degeneration of the tendon that is accompanied by a failed healing process.

The integrative model of tennis elbow proposed by Coombes *et al.* (2009) will be used as a reference theoretical framework in the discussion of the pathogenesis of tennis elbow throughout this thesis. This model follows the principles of reductionism; the complex pathology of tennis elbow is fractioned into smaller entities. Figure 2 illustrates the three factors of tennis elbow pathology according to the new integrative model.

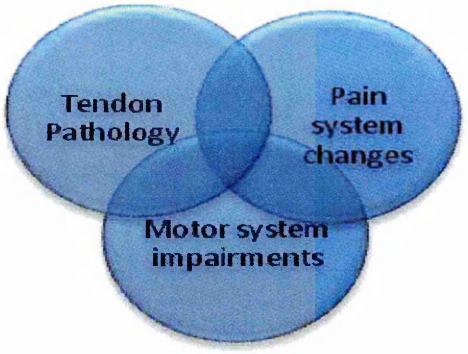

Figure 2: A new integrative model of tennis elbow-multifactorial pathology. Coombes *et al.* (2009)

This integrative model has emerged as a result of the current evidence of the pathophysiology of tennis elbow and it helps to justify developing new therapeutic approaches for tennis elbow. One of the advantages of this model is that it allows for the heterogenic presentation of tennis elbow, because different patients might have different levels of involvement of the three identified systems in the model. For example some patients might have a lot of pain systems changes, other patients might have more motor system impairments or more tendon damage. Therefore, this integrative model challenges current physiotherapy practice because all the current therapeutic approaches are directed toward the tendon pathology. However, it only provides a framework for health professionals where they have to apply effective clinical reasoning to distinguish between different system involvements, identify subgroups of patients with tennis elbow and then direct them to the appropriate treatment. This model is theoretical but it has the potential to evolve and be refined in the light of new emerging knowledge (Coombes *et al.* 2009). The new knowledge emerging from this thesis will add to the understanding of the sensorimotor changes in chronic tennis elbow, the second element in this integrative model. This model will be used throughout this thesis.

Each factor in the integrative model will be reviewed below in the light of the available evidence in order to establish the theoretical framework for this thesis. The first factor of the integrative model is tendon pathology which cannot be fully understood without recognising the anatomy and biomechanics of the elbow region. Therefore, a brief anatomical and biomechanical review is introduced below.

1.1.4 Anatomy of the extensor carpi radialis brevis muscle (ECRB)

In spite of the unclear pathogenesis, histopathological changes were identified at the common extensor origin. The majority of studies about tennis elbow agree that the extensor carpi radialis brevis (ECRB) muscle is very likely to have an integral part in the development of tennis elbow (Stoeckart *et al.* 1989). However, some anatomical studies have questioned this because there is no definitive separation between the ECRB and extensor digitorum communis (EDC) muscles at the osseotendinous junction (Greenbaum *et al.* 1999; Boyer and Hastings 1999). Thus, a brief anatomical

background will be presented about the common extensor origin and ECRB to appreciate the anatomical structure and how it relates to the pathology of tennis elbow.

The common extensor origin is like "one beam" of longitudinal fibrils that are attached together, where the ECRB represent most of the deep fibres (Boyer and Hastings 1999). Figure 3 shows the lateral side of the elbow and the site of the common extensor origin. The tendons of the ECRB and EDC are indistinguishable at the common extensor origin which is why some clinicians claim that it is impossible to attribute the pathology of tennis elbow to ECRB alone (Greenbaum *et al.* 1999; Boyer and Hastings 1999). Nevertheless, the ECRB remains the centre of investigation and discussion in the research around tennis elbow. The ECRB muscle extends the wrist along with the extensor carpi radialis longus (ECRL) and extensor carpi ulnaris muscles (ECU). However, ECRB is noteworthy because it has a smaller bony origin at the lateral epicondyle than ECRL and ECU (Stoeckart *et al.* 1989). Furthermore, ECRB has a fascial origin which is also small in comparison with the extensor digitorum and the extensor carpi ulnaris (Stoeckart *et al.* 1989). The repeated extension actions during pinching and grasping exert forces at the ECRB tendon and origin; repetitive large forces and inadequate biomechanics might make ECRB more susceptible to injury or hinder the healing process after injury (Stoeckart *et al.* 1989). The tendon is the interface that connects the muscle to the bone; therefore, it conveys muscle force to the bone to produce joint movement (Fedorczyk 2006). The vascularity of tendons is poor in general; hence poor healing may develop in some tendon injuries (Fenwick *et al.* 2002).

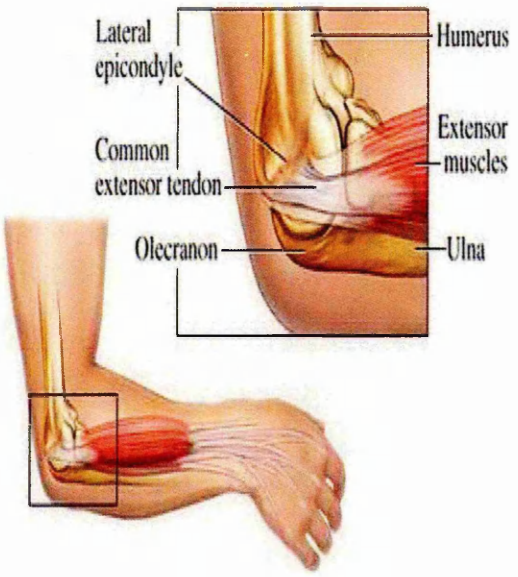

Figure 3: Anatomy of the common extensor tendon (From http://www.health.com)

1.1.5 Biomechanics of the elbow region

The elbow is one of the structures at the distal end of the kinetic chain; this position predisposes its structures to high repetitive forces during different actions like throwing a ball or hitting a tennis serve (Kibler and Sciascia 2004). Biomechanical analysis of the generation and regulation of forces at the elbow joint has been studied in some athletic activities. Research has shown that only 5-10% of patients with tennis elbow are actually tennis players (Boyer and Hastings 1999). However, studying the biomechanical loading in the athletic activities that might cause tennis elbow in tennis players might still provide some insight on the cause and nature of tennis elbow pathology. During different athletic activities, the elbow goes through a large arc of motion in a short period of time with high resultant angular velocity creating varus stress (Kibler and Sciascia 2004). These loads have to be regulated; otherwise, imbalance will create acute or chronic stresses that will develop into injury later (Kibler and Sciascia 2004). The repetitive microtrauma along with degenerative changes and continuous biomechanical demand form a vicious cycle that seems to be responsible for the pathology of tennis elbow (Kibler 1994; Kibler 1995).

As the elbow is part of the kinetic chain, it receives and transfer loads to other structures in the kinetic chain like the shoulder, hip and leg. Therefore, its role cannot be understood in isolation from other proximal and distal structures (Kibler and Sciascia

2004). A problem in the elbow might be compensated by other parts in the kinetic chain; these compensations might be present as maladaptations, previous injuries, muscle imbalance or poor postural alignment. Equally, the scenario could be the other way round, where problems in proximal structures violate the normal biomechanical generation and loading of forces in the kinetic chain, thus leaving the elbow more susceptible to injury (Kibler and Sciascia 2004). Thus the examination of the shoulder, trunk, hip and leg should be considered by health professionals while assessing patients with tennis elbow in order to screen any abnormality and modify their management plan accordingly (Kibler and Sciascia 2004). Physiotherapists who are experts in upper limb musculoskeletal conditions at the Host organisation, Sheffield have for some time been doing screening tests for the shoulder, trunk, hip and leg, and they incorporate core stability exercises for patients with tennis elbow along with the commonly used treatment for tennis elbow. Results have been promising so far (unpublished data/ Host organisation, Sheffield).

1.1.6 The new integrative model for tennis elbow

The new integrative model of tennis elbow is based on the reductionism theory, where a complex problem is reduced into smaller basic elements to make it easier to be understood and analysed (Ahn *et al.* 2006). Reductionism has been the predominant approach of enquiry, diagnosis and treatment in medicine for centuries. Nonetheless, it has its limitations, for example the inability to explain the nonlinear interaction of the components. Therefore, the systems approach is a new perspective of enquiry that addresses the nonlinear component-component interaction and dynamics (Ahn *et al.* 2006a). However, Coombes *et al.* (2009) overcome this limitation by defining their model as an integrative model that comprises three interrelated components, thus their model goes beyond the linear relations between these components. The basic Venn diagram with overlapping circles (Figure 2) used to conceptualise the model also shows the hypothetically possible relations between the different identified pathology components of tennis elbow. Yet it does not show how they interrelate with each other and the proportion of their involvement. It might be difficult with the currently available knowledge about tennis elbow pathology to predict how these components interrelate with each other. But given the chronic nature of the condition and plasticity of the

nervous system, we could at least predict a more complex diagram where time and internal body feedback play a major role in defining the complex pathology of tennis elbow.

The following section will review the three factors of the new integrative model of tennis elbow proposed by Coombes *et al.* (2009). The first factor is tendon pathology.

1.1.6.1 Tendon pathology

For decades tendon pathology has been thought to be the underlying cause of tennis elbow but it does not explain some of the characteristics of tennis elbow like the bilateral sensorimotor deficits and referred pain for example. However, the histopathological and electromyographic studies suggest that there are pathological and dysfunctional changes in the musculotendinous unit of the extensor carpi radialis muscle in patients with tennis elbow (Slater *et al.* 2003). This means that a tendon pathology is present in patients with tennis elbow but it is not the only cause underlying the pathology of the condition, hence the unexplained symptoms of tennis elbow.

In the elbow surgery literature, authors described the cause of tennis elbow as an enthesopathy of the common extensor origin at the lateral epicondyle (Aoki *et al.* 2005). Enthesopathy is a term used to describe the disease at the site of attachment of muscle tendons and ligaments to bony or joint capsules (Benjamin *et al.* 2006). On the other hand, muscle imbalance is another term that is commonly used in biomechanics and sport related literature when discussing the cause of tennis elbow. Tennis players who are diagnosed with tennis elbow constitute less than 5 to 10% of tennis elbow cases but 50% of recreational tennis players will develop tennis elbow (Nirschl 1986). This high prevalence rate could be explained by the fact that novice players tend to strike the ball with a flexed wrist while their experienced peers strike the ball with their wrists more in extension (Eygendaal *et al.* 2007). Moreover; kinematic data and computer models have shown significant eccentric contractions of the ECRB in novice players with low muscle activation at ball impact which could lead to repetitive microtrauma that will develop later to tennis elbow (Riek *et al.* 1999).

Determining the histopathological status of the ECRB tendon could help health professionals to adjust their treatment according to the tendon changes. This is

inherently being done by health professionals by classifying their patients into acute and chronic. Unfortunately, objective measures that are available to assess the histopathological changes in the tendon are limited, for example biopsy is an invasive and impractical method to be used as a routine assessment in the clinic and magnetic resonance imaging (MRI) is not usually done in these patients unless they are due to surgery. Therefore, health professionals do not have the technology for routine histopathological tests (Fedocrzyk 2006; Stasinopoulos and Johnson 2006). The best that could be done by health professionals now in order to establish the histopathological changes is the history of the condition (Fedocrzyk 2006). Where symptoms lasting less than three months are classified as acute tennis elbow and symptoms lasting more than three months are classified as chronic tennis elbow (Fedocrzyk 2006).

Another way of assessing the histopathological changes in the tendon is ultrasound; a new study by Clarke *et al.* (2010) was the first study to correlate the clinical outcomes of tennis elbow with ultrasound images. Ultrasound is one of the imaging modalities that can be used to confirm the diagnosis of tennis elbow and determine its severity (Connell *et al.* 2001); it shows structural changes and blood flow changes. The structural changes of the tendon include tendon thickening, fibroblastic degeneration and heterogenictity. The structural changes could be progressive and reflect the severity of tennis elbow. The findings of the study by Clarke *et al.* (2010) suggest that the degree of tendon tear correlate with the severity of tennis elbow, where patients with large tears identified by the ultrasound are less likely to respond to conservative treatment. Blood flow is another feature that could be assessed using ultrasonography and colour Doppler, increased blood flow or neovascularisation has been found in the tendon of ECRB in patients with tennis elbow (Clarke *et al.* 2010; Zeisig *et al.* 2006). However, it does not correlate with the pain and functional disability of tennis elbow (Clarke *et al.* 2010). This suggests that neovascularisation is not linked to the healing process in the tendon; it is more likely to reflect the chronicity of the condition and is related to pain mediation in these patients (Fedocrzyk 2006).

While discussing the tendon pathology in tennis elbow, we cannot ignore the contribution of the sports medicine literature in understanding the aetiology and

pathophysiology of tennis elbow in athletes. Kibler (1995) suggested a framework to identify the causation of tennis elbow; he called it the negative feedback vicious cycle (Figure 4). The negative feedback cycle is based on Meeuwisse's framework (mentioned under the aetiology section 1.1.2, also see Figure 1), but it differentiates between subclinical adaptations (cellular and tissue changes) and clinical symptoms (pain and weakness of the extensors muscles). For the clinical symptoms to be evident, significant stress and strain have to be placed on the tissue. Despite the fact that repetitive microtrauma might not place the level of stress and strain needed to elicit symptoms, they still have harmful and damaging effects on tendon, muscle and muscle-tendon junction (Kibler 1995). These damaging effects have been identified at cellular and tissue levels; regardless of the different hypotheses of tennis elbow, cellular damage means that the cell is unable to produce a normal shape and size matrix. Clinically observed symptoms are those changes occurring at the tissue level.

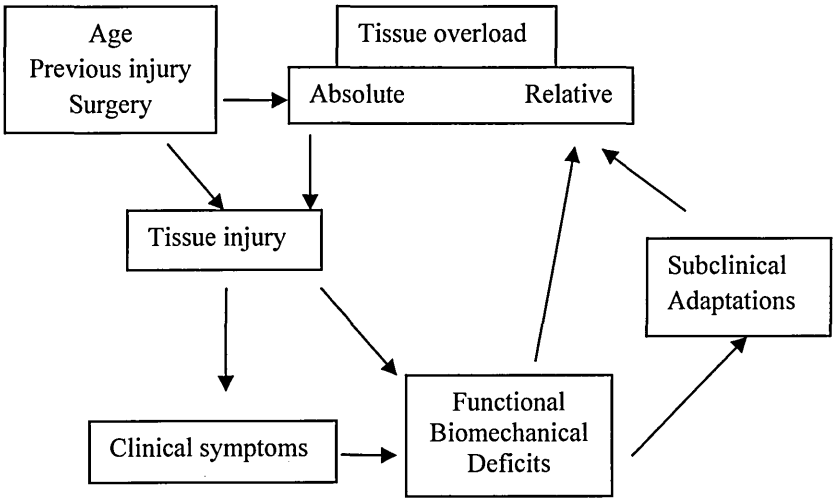

Figure 4: Negative feedback vicious cycle (Redrawn from Kibler 1995).

Taking another perspective, a study of four case series revealed radiological and histological evidence of osteonecrosis of the lateral epicondyle in tennis elbow (Barakat *et al.* 2004). The osteonecrosis of the lateral epicondyle is not explained but it could be due to the poor mechanical pull of the extensor muscles along with continuous biomechanical loading.

Further insight into understanding the tendon pathology in tennis elbow is to observe the findings of tendon changes in other tendinopathies like the patellar tendinopathy and achillis tendinopathy because there are similarities in the symptoms and response to treatment in these conditions (Coombes *et al.* 2009). "Stress shielding" is being more and more accepted as a possible aetiology for tendinopathies. Its underlying theory views the tendinopathy as a combined overuse-underuse injury while the majority of the tensile load being transferred to the superficial portion of the tendon while the deep portion bears too little of that load. Bearing in mind that the deep portion of the tendon is the part that is mostly affected in tennis elbow, this means that low load contributed to the injury. In turn this implies that the common tennis elbow aetiology of tendon overuse is not completely true and it should be replaced by the tendon overuse and underuse model. (Orchard *et al.* 2004).

1.1.6.2 Motor system impairments: sensorimotor and proprioceptive deficits

This is the second factor in the theoretical integrative model. Motor performance is often assessed in patients with tennis elbow; the majority of studies on tennis elbow reported strength assessment. Grip strength is a popular measure of motor performance in patients with tennis elbow; patients tend to have decreased grip strength in their affected arms (Pienimaki *et al.* 2002). However, there are other aspects of motor performance other than strength; sensorimotor function is one of them. Only a few studies have investigated sensorimotor performance in patients with tennis elbow. Pienimaki and his colleagues (1997) were the first to assess sensorimotor function in patients with tennis elbow. They found bilateral increase in reaction time and decreased speed of movement in patients diagnosed with unilateral tennis elbow when compared to sex and age matched control group. Their results showed statistically significant increases in simple, 1-choice and 2-choice reaction times as they were 19% to 36% slower in patients when compared to controls. Speed of movement was also significantly lower in patients by 31%-32%.

The study of Pienimaki and colleagues (1997) showed novel results of sensorimotor deficits present in tennis elbow and therefore added a new dimension to

the understanding of the condition. However, the assessment was done only once with no follow ups, which makes it impossible to judge whether these deficits were primary and made those patients more susceptible to develop tennis elbow or whether these deficits were secondary to the condition itself. Furthermore, patients included in the study were very chronic with duration of symptoms between 15 to 102 months, while the average duration of symptoms is between 6 and 24 months (Smidt and Windt 2006). However, the average duration is usually for patients who have self limiting tennis elbow and therefore, their symptoms will resolve on their own. This justifies including chronic patients in the study but given the high recurrence rate of tennis elbow it might be worthwhile to undertake research with less chronic patients to establish whether they have sensorimotor deficits even after the symptoms had resolved.

Similar results of slower reaction times and decreased speed of movement were found by Bisset *et al.* (2006). Reaction times were slower by 11% to 13% and speed of movement was decreased on average by 2% to 15%. Both results were statistically significant but the reduction was less than reported earlier by Pienimaki *et al.* (1997). The authors claimed that this difference could be due to the different chronicity of tennis elbow, as the median duration of tennis elbow was 31 months in the Pienimakie *et al.* study while it was 4.5 months in the Bisset *et al.* study. Both studies, used the same instrument for collecting the data of reaction time and speed of movement and also used the same protocol, therefore their results are comparable given the fact that the age range and sex distribution were also similar (see Table 2 for studies details). The assessment was carried out by a blinded assessor which eliminated researcher bias on participants' performance.

Following the same argument on reaction time, a recent study by Bisset *et al.* (2009) reported that sensorimotor deficits present bilaterally in patients with unilateral tennis elbow and remain even after treatment. This single blind randomised controlled trial had a large sample size and assessment at base line, 6 and 52 weeks follow-up. With a large sample size it is more likely to have a random sample so it is assumed that the sample is more representative of the population, therefore, the results could be generalisable to patients with tennis elbow who have similar characteristics. The follow up assessment allows tracking changes in sensorimotor function over time, something

that was missing in previous studies. Results showed that although pain resolved and function improved, sensorimotor deficits remained and were not affected by the treatment; however, it should be noted that the treatment was not directed to sensorimotor function. The authors concluded that further research is warranted to investigate sensorimotor function in patients with tennis elbow. The clinical significance of these sensorimotor deficits was not discussed; it could be argued that these deficits might be statistically significant but not clinically significant in the light of Bisset *et al.'s* (2009) findings as other symptoms had improved. It is too early at this point to make a decision about clinical significance even if other symptoms subsided because the recurrence rate is high and the longest follow ups was done at 52 weeks, there is no evidence yet telling us the prognosis after 52 weeks.

All the previous studies investigated gross motor function in patients with tennis elbow. On the other hand, fine motor function was assessed by Skinner and Curwin (2007), who administered two measures of upper limb function: the Purdue Pegboard Test (PPT) and the Complete Manual Dextrity Test (CMDT) to 28 patients with tennis elbow and 28 age, gender and hand dominance matched control group. They found a statistically significant decrease in fine motor function in patients with tennis elbow when compared to the other group. Unlike the other studies, this study included acute and chronic patients with tennis elbow and found no effect of the length of the injury on the fine motor function. The sample size was smaller than the previous studies and participants selection was not randomised which implies that generalisation of the results should be done with caution to populations with similar characteristics. However, sampling bias was minimised by matching patients to age, gender and hand dominant controls.

A conflicting study by Juul-Kristensen *et al.* (2008), investigated the proprioception of the elbow and knee joints in a group of patients with tennis elbow as compared to a control group. Proprioception was assessed using joint position sense and the threshold to detection of a passive movement. Findings revealed reduced proprioception of the elbows in patients with tennis elbow but no differences were found between groups regarding the knee proprioception. The authors interpreted the results in the light of a local muscle injury, and excluded the possibility of a generalised

effect which is in conflict to the findings of Pienimaki *et al.* (1997), Bisset *et al.* (2006) and Bisset *et al.* (2009). However, the interpretation of Juul-Kristensen *et al.* (2008) seems inappropriate given the small sample size (15 patients and 21 healthy controls) and the fact that patients were moderately affected with tennis elbow, the chronicity period of tennis elbow was not reported, the authors only mentioned that 9 patients had pain in the last seven days. The chronicity period is an important aspect to bear in mind when comparing the results of these studies especially as all the previous studies included chronic patients except the study by Skinner and Curwin (2007) who included both chronic and acute patients (acute patients less than 12 weeks). Table 1 shows the chronicity periods in the different studies and Table 2 provides a summary for the studies. Despite the fact that no deficits were detected in knee proprioception, this was the first study to assess the lower limb in patients with tennis elbow in order to investigate any generalised effects of the condition. Therefore, this would suggest a need to conduct further studies with larger sample sizes and identified chronicity of the condition to investigate motor control function of the lower limb in patients with tennis elbow.

None of the previous studies included conclusive interpretation for their findings because of the unknown aetiology and pathology of tennis elbow; nevertheless, those who found bilateral deficits have suggested some explanations. These explanations were either the involvement of a central sensitisation process due to pain or some changes in the somatosensory cortex due to repetitive stereotype movements and pain. Another explanation for the deficits seen bilaterally suggested by Juul-Kristensen *et al.* (2008) was that patients will use their unaffected arm more frequently in order to protect their affected arm. However, this is not likely to be the reason because tennis elbow more commonly affects the dominant arm and patients usually have no other choice except to continue using the affected arm in their work and leisure related activities.

Study	Chronicity of tennis elbow
Pienimaki *et al.* (1997)	median of symptoms in months/ women 30 (20-104), men 31 (15-102)
Bisset *et al.* (2006)	mean in months 7.7± 10
Skinner and Curwin (2007)	mean in weeks 30.54 ± 36.69
Juul-Kristensen *et al.* (2008)	not mentioned (9 patients had pain in the last 7 days)
Bisset *et al.*(2009)	mean in weeks 30.9 ± 29.2

Table 1: Chronicity of tennis elbow in the previous studies.

Authors	Title	Study design	Sample size	Participants age	Gender	Measu
Pienimakie *et al.* 1997	Bilaterally decreased motor performance of arms in patients with chronic tennis elbow.	Cross sectional case control study	32 patients 32 age and sex matched controls	29-54 (mean:43)	21 females 11 males	Sensorimot module of t elements of
Bisset *et al.* 2006	Bilateral sensorimotor abnormalities in unilateral lateral epincondylalgia.	Assessor blinded case controlled study	40 patients and 40 age and sex matched controls	Patients 32-66 (mean 49.5) Controls 33-64 (mean 48.4)	16 females 24 males	Digital grip Sensorimot module of t Elements of and Visual (VAS).
Juul-Kristensen *et al.* 2008	Poorer elbow proprioception in patients with lateral epicondylitis than in healthy controls: A cross sectional study		15 patients 21 healthy controls	Patients: mean 47.8 (SD 7.5). Controls: mean 45.2 (SD 8.8).	only females	
Skinner and Curwin 2007	Assessment of fine motor control in patients with occupation-related lateral epicondylitis.		28 patients and 28 age, sex and hand dominance matched controls	30-53 Patients mean 41.93 (SD 6.44). Controls mean 42.36 (SD 6.44).	16 females 12 males	Subtest of t Pegboard T 32020 and t Turning and the Complet Dexterity T Model 3202
Bisset *et al.* 2009	Sensorimotor deficits remain despite resolution of symptoms using conservative treatment in patients with tennis elbow: a randomised controlled trial.	Single- blind randomised controlled trial	198 patients	18-65	Patients 70 females 128 males Controls 16 females 24 males	Sensorimot module of t Elements of

Table 2: Summary of studies on sensorimotor and proprioception deficits in tennis elbow.

1.1.6.3 Pain system changes

Pain is the third element in the new integrative model of tennis elbow, this section will include introduction to the concept of pain, central sensitisation and the key studies investigating pain and central sensitisation in patients with tennis elbow.

Pain is defined by the International Association for the Study of Pain (IASP) as: "an unpleasant sensory and emotional experience associated with actual or potential tissue damage, or described in terms of such damage" (IASP website). Musculoskeletal pain is "a known consequence of repetitive strain, overuse, and work-related musculoskeletal disorders" (IASP website). The nervous system is plastic and the simplest type of plasticity is that repeated noxious stimuli will develop either into sensitisation or habituation; the latter means decreased response while the former means increased response (Eriksen and Ursin 2004). Central sensitisation has been reported to be the cause of pain in some chronic musculoskeletal conditions like fibromyalgia, back pain and carpal tunnel syndrome (Staud and Smitherman 2002; Zanette *et al.* 2010; Nijs *et al.* 2010). This is supported by evidence of sensory testing, brain imaging and blood tests (Zanette *et al.* 2010). There is an accumulating evidence of experimental and clinical studies that suggests a similar central sensitisation process in patients with chronic tennis elbow (Pienimaki *et al.* 1997; Bisset *et al.* 2006; Bisset *et al.* 2009; Slater *et al.* 2003; Slater *et al.* 2005). The available literature so far investigated the sensory changes and neurotransmitters in chronic tennis elbow, yet, there is no study on brain images in these patients.

Acute pain is thought to be a protective mechanism to prevent further damage which is triggered by noxious stimuli; however, in central sensitisation pain is not protective anymore (Latremoliere and Woolf 2009). It could either flare up spontaneously without any stimuli or it could arise by normal harmless stimulus, this pain is known as allodynia. Also pain could be evoked by noxious stimuli but in an exaggerated and long lasting manner which is known as hyperalgesia, while secondary hyperalgesia refers to the pain that extends beyond the site of injury (Latremoliere and Woolf 2009; Staud and Smitherman, 2002). Hyperalgesia and secondary hyperalgesia are some of the distinctive manifestations of central sensitisation that have been reported in patients with tennis elbow and could be recognised clinically by health

professionals through performing quantitative sensory testing (Graven-Nielsen and Arendt-Nielsen 2002).

Central sensitisation is increasingly being linked to a number of chronic musculoskeletal disorders like fibromyalgia, chronic whiplash and recently carpal tunnel syndrome (Nijs *et al.* 2010). Similarly, it should be addressed in patients with chronic tennis elbow as it might be responsible for the unresolving pain in these patients. The understanding of central sensitisation involvement in chronic tennis elbow will facilitate applying a mechanism based physiotherapy management approach (Graven-Nielsen and Arendt-Nielsen 2002). Although the term central sensitisation is becoming popular between health professionals, its definition, manifestations, ways of assessment and interpretation are still not clearly understood. For the purpose of this review, a brief introduction to central sensitisation is included.

Central sensitisation means pain hypersensitivity due to changes in the central nervous system (Latremoliere and Woolf 2009). These changes alter the way the central nervous system respond to stimuli rather than pain being associated with the occurrence of noxious stimuli (Latremoliere and Woolf 2009). In the language of neurophysiology the central sensitisation refers to the enhancement in the function of dorsal horn neurons and circuits in nociceptive pathways in the spinal cord (Staud and Smitherman 2002). It is caused by increases in membrane excitability, synaptic efficacy and reduced inhibition (Latremoliere and Woolf 2009). It demonstrates that the somatosensory nervous system is plastic and responds to activity, inflammation and neural injury where the pain hypersensitivity is the result of the change in sensory response. Figure 5 is a basic diagram that shows the structures involved in central sensitisation and Figure 6 summarises the mechanisms of central sensitisation.

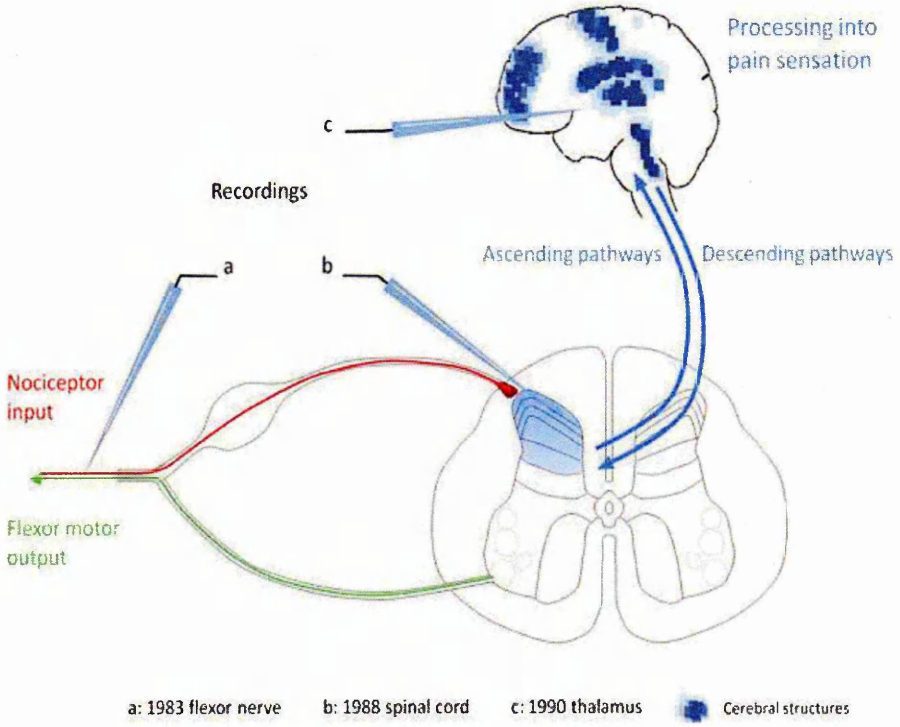

Figure 5: Structures involved in the central sensitisation (Latremoliere and Woolf 2009).

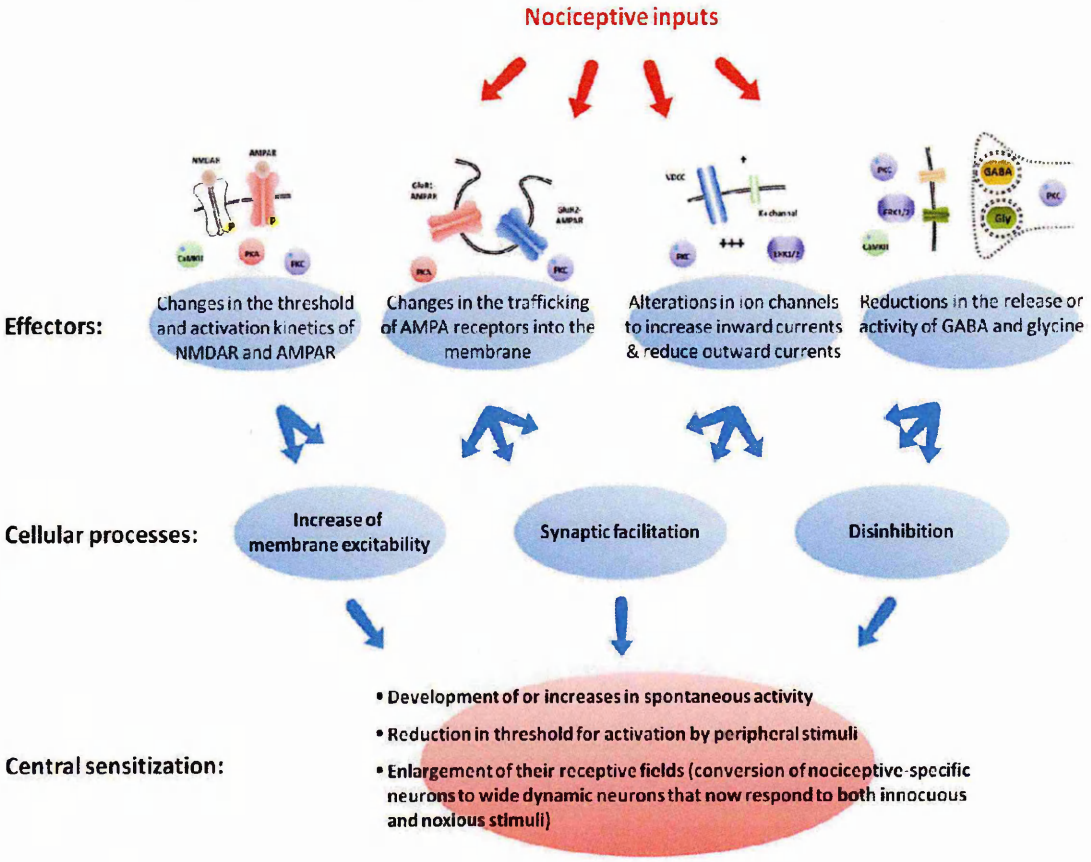

Figure 6: Summary of the mechanisms of central sensitisation process (Latremoliere and Woolf 2009).

It is of paramount importance for health professionals to understand the link between central sensitisation and chronic musculoskeletal conditions in order to be able to detect the manifestations of central sensitisation, assess them and integrate them in the treatment plan. Central sensitisation is a result of the chronicity of the disease because it is a time dependent process and it is usually seen in patients who have had pain for a long period of time (Graven-Nielsen and Arendt-Nielsen 2002). In patients with chronic tennis elbow, it seems that the persistent pain at the affected elbow stimulates the process of central sensitisation then the latter transforms the local pathology to a generalised one (Graven-Nielsen and Arendt-Nielsen 2002). Evidence on the involvement of central sensitisation in chronic tennis elbow is based on the findings of quantitative sensory testing which can be used by health professionals in their clinics to assess the manifestations of central sensitisation (Graven-Nielsen and Arendt-Nielsen 2002). However, unlike other chronic musculoskeletal conditions, evidence of brain imaging in patients with tennis elbow is still not available.

Health professionals might lack the knowledge and experience when it comes to the difference between peripheral sensitisation and central sensitisation; the simplest explanation would be that peripheral sensitisation is only bound to the site of injury itself while central sensitisation spreads outside the site of injury (Graven-Nielsen and Arendt-Nielsen 2002). Another important characteristic of central sensitisation is its role in mechanical sensitivity. While peripheral sensitisation affects heat sensitivity, patients with chronic unilateral tennis elbow presented with mechanical hyperalgesia (Graven-Nielsen and Arendt-Nielsen 2002).

A number of experimental studies have been carried out mimicking the characteristics of tennis elbow which are localised deep tissue pain, hyperalgesia and decreased force of wrist extensors (Slater *et al.* 2003; Slater *et al.* 2005; Fernandez-Carnero *et al.* 2010). The studies design and results are shown in Table 3. Slater *et al.* (2003) did an experimental study on healthy participants to build a human model for tennis elbow by injecting an exogenous stimulus for muscle nociception. Results showed that the most sensitive sites were the ECRL origin and ECRB muscle belly which indicate a higher density of nociceptors and explain why patients with tennis elbow complain from pain and hyperalgesia in these areas (Slater *et al.* 2003).

In another study using the same protocol as the previous study, Salter *et al.* (2005) compared the experimentally induced muscle pain in healthy participants and patients with unilateral tennis elbow. The patients showed earlier onset of pain, longer lasting pain and larger areas of referred pain. Moreover, bilateral increase in the deep tissue sensitivity, all of these suggests an involvement of a central sensitisation process (Slater *et al.* 2005).

The previous results are supported by Fernandez-Carnero *et al.* (2009) who explored the extent of the somatosensory impairments in patients with tennis elbow as compared to healthy controls. A battery of sensory tests was carried out and the findings showed that patients with tennis elbow had bilateral pressure pain hyperalgesia not only in the elbow region but also in their wrists. The bilateral pain in the distant areas suggests that contra-lateral segmental sensitisation has occurred due to segmental central sensitisation of the dorsal horns. On the other hand no significant changes were detected in the other thermal and vibration sensory tests which also indicate that mechanical hyperalgesia is a characteristic for tennis elbow.

A recent experimental study by Fernandez-Carnero *et al.* (2010) applied topographical techniques to map the pressure sensitivity changes in healthy participants who had induced delayed muscle soreness as a model for tennis elbow. The results showed the pressure pain sensitivity maps were heterogeneously distributed and the ECRB belly muscle was the most sensitive point. The finding about the ECRB is in line with previous studies, supporting the role of ECRB in tennis elbow. This study also stimulated further research to investigate the role of eccentric exercises in tennis elbow management. It should be born in mind that only repetitive eccentric exercises were used to induce a model of tennis elbow. However, repetitive eccentric exercises are not sufficient alone to mimic the symptoms of tennis elbow, as repetitive eccentric exercise is presented with hyperalgesia and force attenuation while resting pain does not accompany it (Slater *et al.* 2003). Therefore, resting pain should be induced using another technique such as the saline injection. Interestingly Fernandez-Carnero *et al.* (2010) referred to Slater *et al.* (2003) in the protocol but they did not actually do the combined approach of saline injection and repetitive eccentric exercise recommended by Slater *et al.* (2003).

The studies by Slater *et al.* (2003) and Fernandez-Carnero *et al.* (2010) were performed in healthy populations aged between 22 and 27 years while the age of onset of tennis elbow is usually after 45 years. No control group was included. However the other two studies by Slater *et al.* (2005) and Fernandez-Carnero *et al.* (2009) included a control group that was age, gender and affected arm matched.

Further research that might help to explain the pain mechanism in tennis elbow come from an immunohistochemical study by Zeisig *et al.* (2009). This study suggests that there is an immunohistochemical evidence of local production of catecholamines in the fibroblasts of the muscle origin at the lateral epicondyle in patients with tennis elbow while no evidence of production of catecholamines was found in healthy controls. Catecholamines are a neurotransmitter that can be produced by non neural tissues and might interfere with vasoconstriction of the blood vessels and pain sensation in patients with tennis elbow (Zeisig *et al.* 2009). Although this study is the first to report the production of catecholamines, there are some concerns regarding the sample of patients as they had undergone surgery for their tennis elbow, so it could be argued as to whether the same findings will be found in patients with tennis elbow who did not have any surgery. Table 3 shows the details of the key studies that investigated pain in tennis elbow.

Authors	Title	Study design	Sample size	Participants age	Gender	
Slater *et al.* 2003	Experimental deep tissue pain in writ extensors- a model of lateral epicondylalgia	2 experiments	12 healthy participants	22-27 years mean age 23.9	experiment1 6 males 6 females experiment2 5 males 7 females	Elect (Som Hand strain
Slater *et al.* 2005	Sensory and motor effects of experimental muscle pain in patients with lateral epicondylalgia and controls with delayed onset muscle soreness		20 patients 20 healthy controls	Patients 34-65 mean 48.25 Healthy 32-63 mean 47.45	10 males patients 10 males healthy participants	Elect (Som Hand strain
Fernandez-Carnero *et al.* 2009	Exploration of the extent of somatosensory impairment in patients with unilateral epicondylalgia		12 patients 16 healthy controls	patients mean 47 (10) Healthy controls 41(9)	patients 6 females Healthy 7 females	vibra Swec Ther AB) Elect (Som
Fernandez-Carnero *et al.* 2010	Pressure pain sensitivity mapping in experimentally induced lateral epicondylalgia		13 healthy participants	mean 24.3	13 healthy males	Press Solle

Table 3: Summary of the key studies that investigated pain in tennis elbow.

1.1.7 Therapeutic approaches used in the management of tennis elbow

In this section the main conservative therapeutic approaches used in the management of tennis elbow are presented. All the current treatment methods target the local pathology of the elbow, these treatment methods do not differentiate between subgroups of patients with tennis elbow who might present with different pain and motor deficits. It is important to review current clinical practice used in tennis elbow management in the light of the findings of pain system changes and motor system impairments in order to establish whether there is a gap between science and clinical practice.

Tennis elbow is a challenging condition; although the symptoms might be classified as uncomplicated, they might be persistent in spite of the treatment. Different treatment options are available, ranging from simple conservative techniques to complicated surgical interventions. The main objective of rehabilitation is to relieve the pain and restore the muscles' function. Therefore, treatment directly targets the main symptoms which are the pain and reduced grip function. Although tennis elbow has been known for more than a century, there is no certainty about which is the best approach for treatment; this confusion could be due to the unclear pathophysiology and the lack of well conducted studies (Hong *et al.* 2004). The commonly used conservative treatment options are: non-steroidal anti-inflammatory drugs; corticosteroid injections; wait and see and physiotherapy. The latter involves a variety of techniques such as strapping, friction massage, ultrasound, mobilisation and exercise. Surgical intervention is viewed as the last resort after the failure of all previous conservative options (Dwyer *et al.* 2008).

Corticosteroid injection is a popular method of treatment but evidence shows that it has only a short term effect and patients who undergo injections will have higher recurrence rate in the future. In a single blind randomised controlled trial (RCT) Bisset *et al.* (2006)a compared three treatment options: mobilisation with movement and exercise; corticosteroid injection and wait and see policy. They reported that patients who had corticosteroid injection were significantly better at 6 weeks but had higher

recurrence rates subsequently, while patients who had physiotherapy had better long term outcomes compared to the other groups. The sample size was relatively large (198 patients) with a wide age range (18 to 65) which enhanced the generalisability of the results. An earlier RCT by Smidt *et al.* (2002) investigated physiotherapy, corticosteroid injection and "wait and see" in 185 patients and found very similar results. Although the two studies had similar findings, the physiotherapy program was different, while Bisset *et al.* (2006)a investigated mobilisation with exercise, Smidt *et al.* (2002) investigated pulsed ultrasound, friction massage and exercise. Furthermore, the data from both studies were used to see if subgroups of patients with tennis elbow respond differently to conservative treatment. Results showed that patients responsiveness to treatment were very similar across a heterogenic population which support the generalisability of individual RCT. Another RCT by Bos *et al.* (2004) showed that physiotherapy (ultrasound, friction massage and exercise) is superior to corticosteroid injection and wait and see at 52 weeks. However, the study also involved cost effectiveness analysis that revealed physiotherapy to be costly compared to the other interventions.

Braces are another common treatment for tennis elbow. Struijs *et al.* (2006) conducted an RCT to compare physiotherapy, brace and combination. At one year, follow up success rates were similar but physiotherapy was the most effective. Cost effectiveness analysis also revealed physiotherapy to be cost effective compared to other groups but this was not statistically significant. There are other conservative methods of treatments such as acupuncture and electrotherapy; these were not discussed because they have poor based evidence and sometimes no evidence in the management of tennis elbow (Ruane *et al.* 2010).

This section only reviews conservative methods of treating tennis elbow; however, chronic tennis elbow might require surgery (Boyd *et al.* 1973; Coonrad and Hooper 1973). The success rate of surgery varies extensively in the literature, ranges as low as 50% and as high as 90% being reported in different surgical interventions (Dwyer *et al.* 2008; Khan *et al.* 2007). This means that surgery is not a perfect treatment for patients with chronic tennis elbow; it also suggests that chronic tennis elbow is not solely tendon pathology.

Sub grouping patients with tennis elbow according to their chronicity and symptoms has been suggested by Coombes *et al.* (2009) and Fedocrzyk (2006). The aim of sub grouping patients with tennis elbow is to enable health professionals to deliver and prioritise the treatment appropriate for the presenting symptoms. However, classifying patients with tennis elbow is not straightforward. Tendon changes for example would be better diagnosed by biopsy, which is an invasive and impractical method or MRI which is not usually done in these patients unless due to surgery (Fedocrzyk 2006). The best that could be done by physiotherapists in order to predict the histopathological changes is the history of the condition (Fedocrzyk 2006). On the other hand, the involvement of central sensitisation could be more objectively assessed by quantitative sensory testing. Health professionals attempting to classify patients with tennis elbow should assess the involvement of tendon changes, sensorimotor deficits and pain system changes. Some researchers are still predominantly focussed on tendon pathology and only refer to the histopathological changes of the tendon when talking about tennis elbow classification like Fedocrzyk (2006).

1.1.8 Is the management of chronic tennis elbow evidence based?

Having reviewed the literature underpinning the current management of tennis elbow, this section evaluates the current management and how it fits in the principle of evidence based practice. It also highlights the clinical reasoning of pain performed by physiotherapists while treating patients with chronic tennis elbow.

Evidence based practice is the application of best care to patients according to the best available research evidence; this implies sometimes a change to the traditional treatment (Jette *et al.* 2003). It is noted that treatment options for tennis elbow are directed toward the local muscle pathology, bearing in mind the integrative model of tennis elbow proposed by Coombes *et al.* (2009), this approach of treatment addresses only part of the problem. Slater *et al.* (2005) concluded that the management of patients with chronic tennis elbow needs to address the normalisation of the sensitive nervous system thus stretching the boundaries of the current treatment from being directed to the localised tissue pathology. Although accumulating evidence suggests central

sensitisation process in patients with chronic tennis elbow, this evidence is not being taken on board by health professionals. In a recent report; Nijs *et al.* (2010) discussed central sensitisation in patients with musculoskeletal pain and how to apply pain neurophysiology in manual therapy practice. However, they did not mention tennis elbow at all in their master class report which reflects the lack of integrating research findings of chronic tennis elbow in the management of the condition. A possible explanation for the discrepancy between research findings and clinical practice could be that health professionals are not aware themselves of new research findings, or it could be that they do not have the appropriate knowledge and skill to translate findings of the neurophysiology literature into their management approach. Moseley (2003) identified two barriers that make health professionals unable to reconceptualise the problem in chronic pain. The first barrier is their poor knowledge of up to date accurate information about the neurophysiology and management of pain and the second barrier is that they underestimate the ability of their patients to understand the neurophysiology of pain. Whichever is the case; this violates the essence of the evidence based practice because the best research evidence is not being considered in the clinical process (Moseley 2003).

Another reason that might explain the failure of health professionals to diagnose and treat central sensitisation in patients with tennis elbow is the absence of clinical criteria that define central pain. Smart *et al.* (2010) conducted a Delphi study to establish clinical criteria for central pain through expert consensus, where consultant physicians in pain medicine/ anaesthesia and specialist musculoskeletal physiotherapists developed a set of clinical indicators for central pain. These clinical indicators included: pain persisting beyond expected tissue healing/pathology recovery times, positive findings of hyperalgesia (primary and secondary), more constant unremitting pain and a history of failed interventions. Interestingly, these clinical indicators are common findings in patients with chronic tennis elbow, which suggests again that health professionals have to consider central sensitisation during the management of these patients.

The future of effective tennis elbow management should integrate the findings of the research into the treatment methods, especially for those patients who develop

chronic tennis elbow. Pain education is another aspect that is worthwhile to look at in the patients who have chronic tennis elbow as patients with chronic back pain had decreased pain after the biology of their pain was explained (Moseley *et al.* 2004). However, pain education should embrace the basics of modern pain neurophysiology and not the structural model pathology; because the latter does not provide answers for chronic pain (Moseley *et al.* 2004). The medical model of structure/ pathology oriented explanation is directing the process of clinical reasoning in physiotherapy practice and clinical reasoning in tennis elbow is not an exception (Moseley 2007). However, in a study by Smart and Doody (2007), experienced physiotherapists showed a dynamic and multidimensional process of clinical reasoning where they embraced the following aspects of pain based clinical reasoning: biomedical, psychosocial, pain mechanism, chronicity and irritability/severity. The clinical reasoning style shown in this group of experienced physiotherapists addresses the holistic approach of patient's management. Unfortunately physiotherapists and health professionals in general seem to be in favour of the medical model of structure/pathology and consequently they are prone to miss some of the important aspects of the patients' problem because they cannot see the holistic multidimensional picture. No study has been done to explore the clinical reasoning style in physiotherapists when they diagnose and treat tennis elbow. However the currently used therapeutic approaches clearly reflect a medical model of structure and pathology. This again explains why the key role of central sensitisation is missed.

Moreover, pain education is an integral part of the biopsychosocial approach which is increasingly being linked to the understanding and treatment of chronic pain disorders (Gatchel *et al.* 2007). The biopsychosocial approach conceptualises pain as a multifactorial feature that involves physiological, psychological and social factors; these factors influence the clinical presentation of pain (Gatchel *et al.* 2007).

The innovative treatment approaches of normalising the sensitive nervous system and pain education mentioned in this section are theoretical and based on the research findings in the area of chronic tennis elbow. Up till this point the effectiveness of these therapeutic approaches in patients with tennis elbow were not investigated yet. Although the effectiveness of treatment is beyond the scope of this thesis, future research around chronic tennis elbow should focus on this area.

1.1.9 Summary

The following issues have arisen from this literature review:

- Tennis elbow is a common problem of the upper limb that can be challenging and resistive to treatment.
- The aetiology and the pathology of tennis elbow are still not clear but a multi-factorial pathology is suggested where tendon pathology, sensorimotor impairments and pain system changes contribute in varying proportions to the overall presentation of tennis elbow .
- Sensorimotor deficits are present bilaterally in the upper limbs of patients with unilateral tennis elbow and remain even after treatment which suggests a central sensitisation process.
- Mechanical hyperalgesia is reported bilaterally in the upper limbs of patients with unilateral tennis elbow which also suggests a central sensitisation process.
- The main aim of tennis elbow management is to relieve the symptoms of pain and decreased strength. Different therapeutic approaches are available but there is no consensus on an effective way of management.
- The failure of the current treatment to resolve tennis elbow in some patients may be due to a lack of understanding of tennis elbow pathology.
- The discrepancy between research findings on bilateral deficits of sensorimotor, proprioception and hyperalgesia and clinical management of tennis elbow violates the principle of evidence based practice.
- Tennis elbow is no longer viewed as a local muscle pathology; evidence shows that it is a chronic condition that involves peripheral and central sensitisation processes.
- Central sensitisation has been investigated locally and bilaterally in patients with tennis elbow, while generalised central sensitisation remains a very under-researched area.

1.1.10 The Gap in the literature

Although different studies suggested that tennis elbow is a chronic condition that involves peripheral and central sensitisation processes, bilateral sensorimotor and pain changes of the upper limb have been the focus of the previous research studies. The research on generalised sensorimotor, or pain changes is scarce as only one study was performed to assess the sensorimotor function of the lower limb. However, that study investigated the proprioception of the elbows and knees in patients with tennis elbow and its findings are not conclusive because it involved patients who were moderately affected while previous studies included chronic patients. Moreover, it seems more relevant to investigate the response time of the lower limb in patients with tennis elbow because it was measured repeatedly in the upper limbs of these patients in the previous studies where bilateral deficits have been found. Therefore, studies on response time in the lower limb in patients with chronic tennis elbow are warranted to investigate the hypothesis that generalised sensorimotor deficits occur in these patients.

It can be seen from this review that there are a number of gaps in the literature; firstly, sensorimotor deficits have only been investigated in the upper limb of patients with tennis elbow although generalised sensorimotor deficits have been suggested. Secondly, response time and speed of movement are only one aspect of sensorimotor function. Balance is another aspect of sensorimotor function that has not been investigated yet in patients with chronic tennis elbow but clinical observation suggests that these patients have poor balance when assessed. Moreover, it could be argued that balance is more clinically relevant as it could be easily measured while response time could be rather difficult to measure in a clinical setting. It is the intention of this research to add new knowledge to the field of sensorimotor function in chronic tennis elbow by investigating balance and response time of the lower limbs.

This review also revealed that the knowledge emerging from studies on sensorimotor function in patients with chronic tennis elbow are not being translated into clinical practice. This research seeks to address this discrepancy and bridge the gap between science and clinical practice by providing new knowledge to physiotherapists who are involved in the management of chronic tennis elbow.

The next two sections will review the literature on the outcome measures used in this study. The review presented here aims to identify the rational for measuring balance and response time in this study, their relevance to patients with chronic tennis elbow and why they were selected to be investigated in these patients.

1.2 Balance and Postural control

The first outcome measure is balance and postural control. There are two reasons behind assessing balance in this study. Firstly, evidence has shown that patients with unilateral chronic tennis elbow have bilateral sensorimotor deficits suggesting a central sensitisation process. It is unknown whether these sensorimotor deficits are present in the lower limb. Only one study was conducted assessing the sensorimotor function of the lower limb but that study investigated proprioception of the knee joints. Balance is an important aspect of sensorimotor function and therefore it is justified to be assessed in patients with tennis elbow. Secondly, clinical observation reported by experts in tennis elbow management at the Host organisation, Sheffield, UK. Who observed that patients with tennis elbow tend to have poor balance when they were asked to stand on one leg. Clinical observation is an important factor that stimulates research, although this role is not as central as it used to be because research evolved to be an entity of its own (Probst and Harris 2009; Buckwalter *et al.* 2001). Clinical observation and the curious questions raised by expert health professionals should remain challenging and inspirational sources for research (Buckwalter *et al.* 2001).

Another aspect of the relevance of balance assessment in patients with tennis elbow is based on evidence of distorted body image in patients with chronic pain syndromes like complex regional pain syndrome, phantom limb pain and chronic back pain (Moseley 2008). The pathology of these conditions and tennis elbow is totally different but they all share the experience of chronic pain and they are musculoskeletal conditions that have neurological involvement. The distorted body image affects the feedback process of the sensorimotor system and therefore this might have an impact on the postural control system. The hypothesis of distorted body image in patients with tennis elbow is speculative but it is worthwhile to be considered, however it needs to be investigated properly in these patients.

This section will review the definition, neuroanatomy, assessment and the outcome measures of balance. In the study presented in this thesis, balance measurement was conducted using a force platform which is not usually used by health professionals. One might argue against the use of a non clinical method for balance measurement, however, single leg standing was used in this study and it is one of the most common tests used by health professionals. The clinical assessment of balance in single leg standing usually includes observation skills and timing in the popular Romberg test. The clinical assessment is basic and might indicate the presence of balance deficits. Using a force platform is a necessity in this study and similar balance research because it enables us to analyse balance objectively and in more depth.

1.2.1 Definition

Balance, equilibrium, stability and postural control are common terms, sometimes used synonymously. A number of different definitions can be found for each of the previous terms but despite the differences, they all reflect the same concept. These different definitions reflect the different backgrounds of people working in the area, whether they are interested in biomechanics, kinesiology, physiotherapy, physical medicine or rehabilitation. According to Pollock *et al.* (2000) health professionals have an intuitive understanding of these terms. However, establishing a definition which is accurate, concise and clinically relevant to physiotherapy practice is a key in the process of precise assessment and treatment of patients.

There are two types of definitions; constitutive and operational definitions. The former describe the meaning or the content of a concept by using other concepts while the latter describe the tasks and functions necessary to measure that concept (Ragnarsdottir 1996). The following review of the different definitions of balance and postural control involves mainly constitutive definitions. The operational definition will be reviewed later in the assessment tools section.

Balance is the ability of the individual to maintain the line of gravity within the base of support (BOS) and thus prevent falling (Pollock *et al.* 2000) or the ability to control the gravitational forces to maintain posture and control the acceleration forces to maintain equilibrium (Huxham *et al.* 2001). Alternatively, balance can be defined as a

state of equilibrium (Galley and Forster 1982). It seems that balance is strongly linked to equilibrium as all the previous definitions include equilibrium.

Postural control is the act of maintaining, achieving or restoring a state of balance during any posture or activity, through predictive and reactive strategies (Pollock *et al.* 2000). Equally, it is the ability to control the body's position in space in order to achieve orientation and stability (Shumway-Cook and Woollacott 2011). The latter definition encompasses two functions of postural control; orientation and stability. Orientation means that the relationship between body segments, the body and the environment is properly maintained, and stability is the ability to maintain the centre of mass (COM) inside the BOS (Shumway-Cook and Woollacott 2011).

It is important to keep in mind that increased sway does not necessarily mean a state of disequilibrium but could be a disturbance of postural control. From the previous example Ragnarsdottir (1996) concluded that equilibrium should not be the same concept as balance and postural control because disequilibrium does not equal postural control disturbance. The importance of setting a clear definition is to avoid confusion and misinterpretations. Therefore, balance and postural control should not be viewed as a single task nor as one system function, they are a dynamic multisystem framework that has neural and biomechanical bases. (Shumway-Cook and Woollacott 2011).

The interrelation between postural control, balance, equilibrium and stability is demonstrated in Figure 7. Postural control is the largest concept that encompasses the other concepts, therefore, it will be used throughout this thesis. However, balance is commonly used by health professionals and patients so it will be used in this thesis as well.

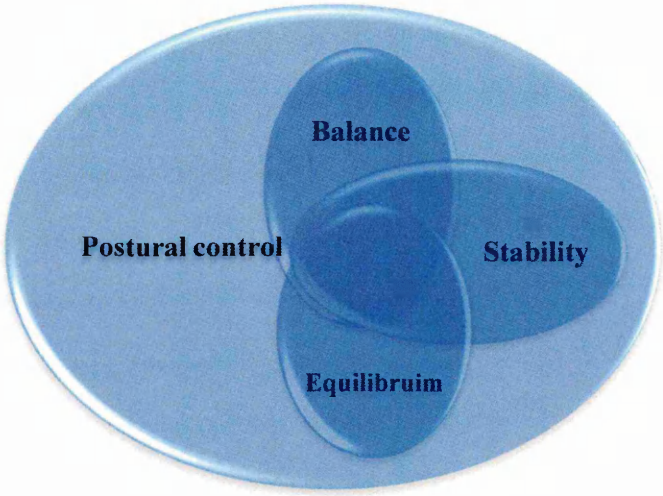

Figure 7: The inter-relations between balance, postural control, equilibrium and stability. Postural control is the largest concept that encompasses the other three concepts.

Postural control is reviewed in more detail in the following section, including theories, neuroanatomy and outcome measures.

1.2.2 Theories of postural control

It is important to be familiar with the theories of postural control in order to interpret the findings of postural control assessment. The theories of postural control are based on the theories of motor control, the most popular ones are: the reflex theory, the hierarchical theory, motor programming theory, ecological theory and systems theory (Shumway-Cook and Woollacott 2011). These theories emerged from physiology, biology and psychology sciences, therefore, their principles and focus points are different. Next, these theories will be reviewed in a chronological order to illustrate how the knowledge has developed over the years. However, it should be born in mind that there is no one best theory, all the theories contributes to the understanding of postural control. While recent theories have broadened and refined our knowledge about postural control, older theories still apply in their context.

One of the earliest theories was the reflex theory, which was first described by Sherrington in the late 1800s. The principle of this theory is that the movement behaviour is based on reflexive reactions which require a receptor, conductor and an effecter. However, there are a number of limitations associated to this theory as it does not explain the voluntary movements because the reflex needs an external stimulus. It

also does not explain fast movements where there is no time for feedback to occur. Moreover, it ignores the role of the environment on movement because one stimulus could result in different movements depending on the context (Shumway-Cook and Woollacott 2011).

Following the reflex theory, the hierarchical theory was developed by a number of researchers. According to this theory, the nervous system is organised in a hierarchy, where the higher centres control over the lower centres in what is called a "top down" fashion. However, this theory does not explain why motor function is sometimes dominated by reflexes in normal individuals, known as the bottom-up control like withdrawing the leg when stepping on a nail (Shumway-Cook and Woollacott 2011).

As knowledge expanded, Motor programming theories emerged; the most distinctive aspect of motor programming as compared to the previous theories, is that the central nervous system is not being viewed only as a reactive system. The movements could be generated without the need for a sensory feedback. However, the environmental effect on the movement is not taken into account which is considered as a limitation.

The systems theory or the dynamic systems theory was first described by Bernstein in the 1960s, which looked at the body as a mechanical system that has redundant degrees of freedom. These degrees of freedom have to be controlled in order to produce movement. This theory recognises the role of the musculoskeletal system, gravity forces and inertia in producing movement. It also acknowledges the inherent variability of the movement while other theories such as motor programming viewed variability as an error. Although the knowledge of postural control theories has extensively developed since the reflex theory, the systems theory has its own limitations. The mathematical formulas and body mechanics dominate the principles of this theory, giving less emphasis on the role of the nervous system (Davids *et al.* 2003).

The ecological theory was developed by the psychologist Gibson (1966). According to this theory, perception detects information in the environment that is needed to perform the movement; therefore, actions are goal directed within the context of the environment. The limitation of this theory is that it is less focussed on the

function and complexity of the nervous system in favour of the interaction between the body and the environment.

All these theories should be taken into account in order to provide a holistic approach for postural control by describing the movement as an interaction between the individual, the task and the environment. Therefore, the postural control encompasses perception, cognition, action systems and the dynamic interaction between them. In order to cover the complexity of the postural control function, the factors that shape its characteristics have to be addressed. These factors could be generally divided into individual related factors, the specificity of the task and the environment (Horak 1997; Rogind *et al.* 2003). Firstly, the individual related factors which include age, gender, expectations and health conditions or disability. Secondly, variations in the task could be endless but might include, changing the speed of walking or running, wearing high heels, walking on a line or on tip toes. Finally, environment factors that could influence the postural control could be the texture of the ground; whether solid or slippery, and lightning to name a few. The task and environmental characteristics affect postural control by altering the biomechanics and the amount of information to be processed (Huxham *et al.* 2001).

Postural control is a complex process that requires multiple systems to work together. The body receives sensory information from the visual system, vestibular system and somatosensory systems (proprioceptive, cutaneous and joint receptors). This flow of sensory information provides an internal representation of the external world. This internal image is not an exact copy but rather a construction of components of the sensory stimuli after being analysed by the brain (Kandel *et al.* 1995). The brain uses the sensory information to create a frame of reference for postural control regarding the position and the motion of the body. This frame of reference could be recalled later to map other similar tasks against it (Kandel *et al.* 1995). Different senses provide different references to the nervous system; visual information provides a reference of verticality, somatosensory information provides a reference in relation to the supporting surface while vestibular information provides a gravitational reference according to the head position (Kandel *et al.* 1995).

Postural control uses the sensory information to function effectively. However, the nature of the task and the environment might make postural control rely more on certain sensory information while the other became less important; for example during standing while eyes are closed, the postural control will depend on the somatosensory and vestibular system to maintain balance. Sensory information might be inaccurate or misinterpreted by the brain because our brain is not able to differentiate between self motion and external motion; sometimes this happens when two cars stop at traffic light and one of them moves, people in the other car will think their car is moving (Shumway-cook and Woollacott 2011).

This internal image is used by the motor system to produce movement which can be classified into three components: reflex, rhythmic motor patterns and voluntary movements. These movements are controlled by the lower and higher motor centres; the former includes the spinal cord and brain stem while the latter is the motor cortex. Reflexes are controlled by the spinal cord, while rhythmic patterns are controlled by the brain stem and new movements are controlled by the motor cortex. The movements controlled by the motor cortex are characterised as goal directed and learned (Kandel *et al.* 1995).

Postural control involves lower and higher centres depending on the activity; an example of reflexes could be stepping on sharp objects when the leg will automatically be withdrawn. Walking and running are examples of rhythmic patterns as the body is used to do these activities, on the other hand, trying to balance standing on one leg involves voluntary movements because it is an unusual activity. However it is important to realise that within this voluntary movement there are ankle and hip strategies which are involuntary movement patterns used to maintain balance (Shumway-Cook and Woollacott 2011).

The relationship between sensory and motor systems is complex, it is important to appreciate that this process is not a linear step by step process, the messages to and from the systems involved are continuously active forward and backward. One way to unveil how they work is to understand the process of coding components of movements in the nervous system and the process of encoding sensory stimuli by the sensory systems (Kandel *et al.* 1995). It is also crucial to realise that cognition is not only about

the internal modelling, it also involves attention and confidence (Shumway-Cook and Woollacott 2011).

Figure 8 illustrates in a very basic way the different systems responsible for maintaining the postural control in single leg standing; all these biomechanical, sensory, motor and central nervous system components are involved in a coordinated manner.

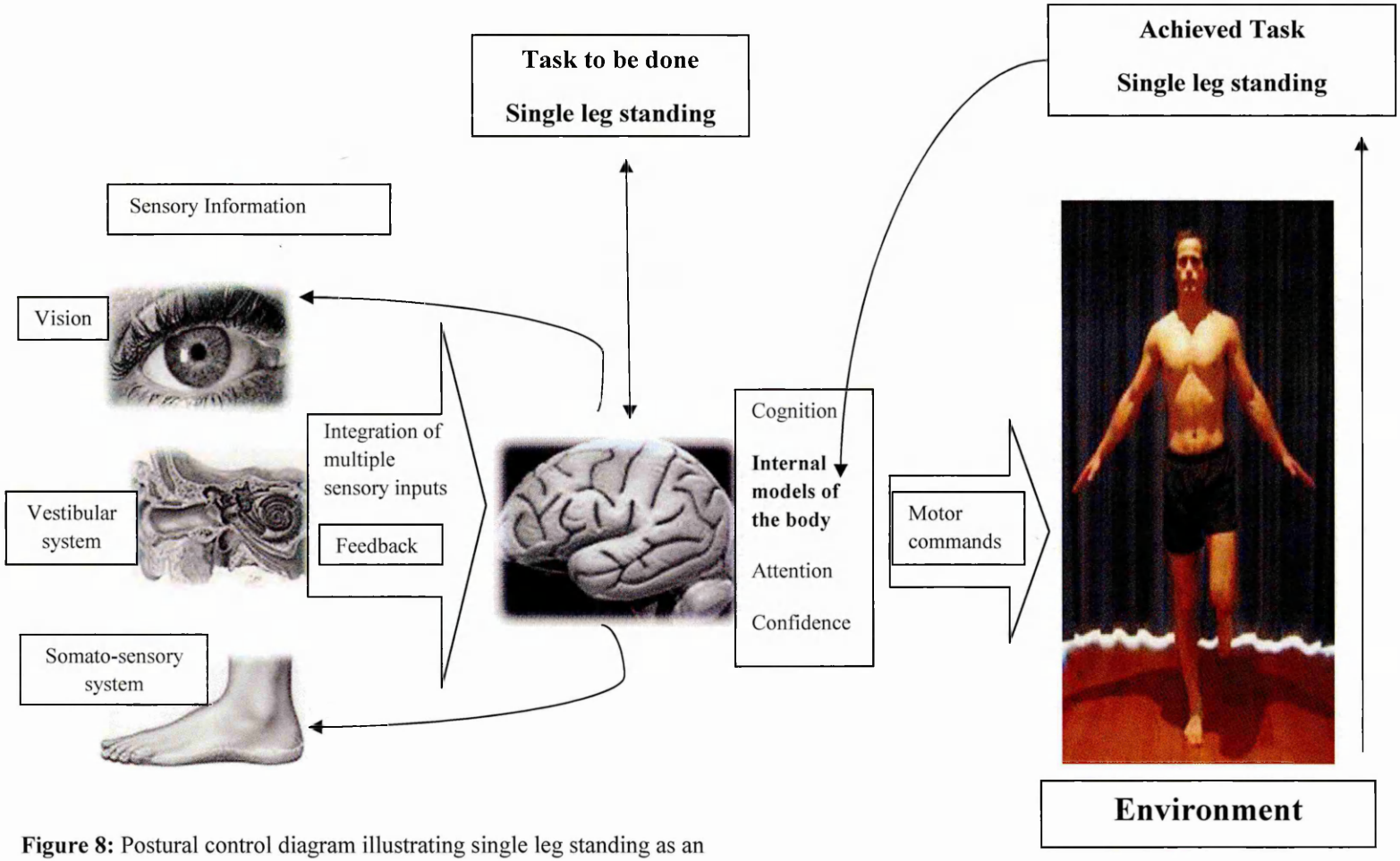

Figure 8: Postural control diagram illustrating single leg standing as an example.

1.2.3 Postural control in standing

Balance and postural control should not be studied, assessed or treated in isolation; they are embedded in an extensive range of functions and tasks that enable the individual to perform activities of daily life (Huxham *et al.* 2001). Activities such as standing, sitting, running, pushing and pulling, regardless of how simple or complicated they seem to be, all involve a complex integrating feedback from the visual, sensory, vestibular and somatosensory centres in the brain, thus, the postural control system is complex and requires the musculoskeletal system and the neural system to work in harmony (Noda *et al.* 2005).

Upright stance is controlled by keeping the centre of gravity (COG) above the base of support. Muscles of the trunk, lower limbs and neck contract to make the body rigid, as a result of these contractions, oscillations occur about the vertical axis. These oscillations are known as postural sway which can be measured using different methods (Rogind *et al.* 2003). It should be born in mind that upright posture is usually attached to other tasks like reaching to a shelf or picking up something (van Emmerik and van Wegen 2002). For the purposes of this study the focus of the review will be on postural control with a steady base, as participants will be performing single leg standing on a stable force platform.

Sometimes, balance is divided into static and dynamic, where static refers to still standing and dynamic refers to any posture that involves movement. However, this classification is argued not to be completely precise because even in still standing there are some postural sways which are literally continuous corrective movements around the centre of gravity (Ragnarsdottir 1996).

A review of postural control outcome measures is presented next. However, the majority of health professionals are not necessarily involved in this kind of balance assessment. Therefore, the review is aimed to help the health professionals audience understand this method of balance enquiry and appreciate its complexity and importance as a rigorous, objective way of assessing balance where its findings could help inform clinical practice in some conditions.

1.2.4 Postural control outcome measures

Before reviewing postural control outcome measures, centre of gravity (COG), centre of mass (COM) and centre of pressure (COP) should be thoroughly understood. They are usually misinterpreted and sometimes used as synonyms. It is important to understand the definition of each term and the differences between them prior to the assessment of balance and postural control, otherwise, misleading or false conclusions could be drawn (Winter 2005; Palmieri *et al.* 2002).

1.2.4.1 Centre of gravity (COG), centre of mass (COM) and centre of pressure (COP)

The COG or the COM is an imaginary point in the body where all forces acting upon it are balanced, or the point around which the mass and weight of the body are balanced (Adrian and Cooper 1995; Hall 2007). While the COP is the weighted average of all the pressures between the supporting surface and the body area in contact with the surface and COP movement is the neuromuscular response to imbalances in the COM (Winter 2005).

People are not consciously aware of the positions of COP and COM. However, they are aware of their limit, that's why an individual will take a step if the COM exceeds the stability limit (Winter 2005). Both COM and COP are used in the assessment of postural control but COP and its derivatives are most frequently used in research (Palmieri *et al.* 2002). It is important to realise that COM is the controlled parameter while COP is the controlling parameter. Some studies use the term postural sway which might be also confusing; it represents changes in COM and therefore, should not be used in regard to the COP (Palmieri *et al.* 2002).

1.2.4.2 Postural control indicators: measures of COP

There are many force platform parameters that can be used to measure balance and postural control, COP parameters are commonly used ones. These parameters are sometimes known as the traditional COP measures because there are new measures for COP that will be discussed later in this section. When selecting the force platform parameters, one should be aware of the reliability, validity, sensitivity and the task being

assessed. Different studies use different force platform parameters, different BOS, different visual conditions, different cognitive tasks, different head and body positions and different length of test and rest time. All these variables make it very difficult to compare different studies with each other; previous studies stressed the importance of standardisation of the methods (Goldie *et al.* 1989; Geurts *et al.* 1993). Next is a brief review of a number of main traditional COP parameters.

One of the commonly used COP parameters is the total excursion of the COP or the sway path which is the total distance travelled by the COP during the trial. The interpretation of this parameter varies in the literature, often an increase in the total excursion (TE) of the COP represents an increase in instability. However, a large TE COP can be found in stable postures, and in this case the COP is making big excursions or a series of small excursions in order to maintain the balance (Palmieri *et al.* 2002).

Another popular parameter is the root mean square amplitude (RMS) and the root mean square velocity (RMS velocity). Both are reliable measures (Guerts *et al.* 1993), and both are documented to be sensitive to proprioception and vision (Niam *et al.* 1999 referenced in Palmieri *et al.* 2002). Guerts *et al.* (1993) reported that the RMS velocity had the highest intra-subject consistency and sensitivity out of the following measures: RMS amplitude, peak to peak amplitude and mean frequency (during different visual and cognitive tasks). The RMS and the RMS velocity are able to detect changes in the ap and ml directions, this is important in order to not to miss any postural impairments (Palmieri *et al.* 2002). However, the use of the RMS amplitude and velocity should be done with caution because the link between the variations detected in both measures and the changes in the postural control system is not established yet (Palmieri *et al.* 2002).

Some studies have used other parameters like the minimum amplitude, maximum amplitude and peak to peak amplitude. All are 1-dimensional parameters because they use only single points out of the thousand points collected so this might misrepresent the data. Another problem could be exaggerated maximum amplitude due to noise, which might lead the researcher to draw inappropriate conclusions of less stability (Palmieri *et al.* 2002).

COP velocity which is sometimes referred to as the mean or average velocity of displacement or the mean total velocity, is reliable in double stance and it is sensitive to change in the visual conditions (eyes closed and opened). It also has the smallest reproducibility error (standardised intra-individual coefficient of variation) (Palmieri *et al.* 2002; Raymakers *et al.* 2005). According to Raymakers *et al.* (2005), it is the most informative parameter in most situations. While Lafond *et al.* (2004) found that the mean velocity was the most reliable measure out of the following measures (RMS, COP range, COP mean velocity, mean power frequency, median power frequency and sway area), with two repetitions needed for reliable measure. However, the previous study involved elderly people over 60 years of old who performed double stance with eyes opened standing on two platforms. According to Salavati *et al.* (2009), total mean velocity demonstrated high to very high reliable data in a group of patients with different musculoskeletal disorders. Participants performed double stance with eyes opened and eyes closed. Benvenuti *et al.*, (1999) reported that COP velocity did not change during different levels of disequilibrium in an elderly group during quiet standing. They explained that COP measures show the level of ankle control while the effectiveness of this control is measured by the COG velocity.

Another less frequently used parameter is spectral frequency analysis which is different than the previous measures because it identifies a frequency range in which the sensory system is functioning. Different sensory systems will have different frequencies and different tasks might increase the demand on specific sensory system (Palmieri *et al.* 2002). Phase plane portraits are rarely used in research studies but Salavati *et al.* (2009) reported that it has high reliability especially in the anterioposterior (ap) and mediolateral (ml) direction in patients with musculoskeletal disorders.

Although these COP parameters are widely used in the literature, they are either 1 or 2 dimensional (combination of the ap and ml movements) measures and authors always recommend not using these parameters solely to evaluate postural control (Palmieri *et al.* 2002). That is why it is important to consider other parameters to assess the postural control. For the purposes of this study, the traditional COP parameters will not to be used. Instead, time to boundary (TtB) will be the main postural control

outcome measure in this study. The definition, rationale of TtB and why it is appropriate for this research are reviewed in the following section.

1.2.4.3 Spatial measures vs. spatio-temporal measures

Postural stability is usually assessed using traditional spatial parameters of the COP and COM, where larger amounts of COP and COM excursions are interpreted as signs of postural instability (Haddad *et al.* 2006; Hertel and Olmsted-Karmer 2007). However, there is an increasing argument against the way the postural instability has been defined using these traditional measures. This can be clarified in the light of some recent studies where young individuals may show more postural sway when compared to a group of elderly or patients with an anterior cruciate ligament (ACL) injury under specific conditions (van Emmerik and van Wegen 2002). Therefore, depending on spatial measures alone in examining postural stability might be misleading (Haddad *et al.* 2006).

1.2.4.4 Time to Boundary

Time to boundary (TtB), time to contact (TtC), virtual time to contact (VTC) or virtual time to collision (VTC), different studies might use different terminologies but all stands for the same concept (Haddad *et al.* 2006). TtB is another measure of postural stability that incorporates both spatial and temporal features of postural control. It is defined as the time estimated for the COP or COM to reach the boundary of the BOS if it continues on its trajectory at its instantaneous velocity. Therefore, smaller TtB measures indicate larger postural instability because an individual is vulnerable to fall when the COP is closer in time to hit the boundary of the base of support (BOS) (Haddad *et al.* 2006; Hertel and Olmsted-Karmer 2007; Hertel *et al.* 2006). The term time to boundary will be used through this thesis rather than time to contact because no contact is likely to occur between the COP and the stability boundary (van Emmerik and van Wegen 2002). The origin of the TtB refers back to the work done by Lee (1976) and Lee *et al.* (1983) on the visual timing in hitting an accelerating ball; they defined that variable as tau (τ): "the time remaining before contact with an object if the closing velocity is constant". According to Lee *et al.* (1983) continuous TtB information is

crucial to locomotion activities. The TtB is an adaptation of the tau (∏) control variable used by Lee (1976).

TtB takes into account the temporal characteristics like velocity and sometimes acceleration depending on the method of calculation in addition to the spatial aspects (displacement). The temporal characteristics are not addressed in most of the traditional measures of COP and COM (Haddad *et al.* 2006; Hertel and Olmsted-Karmer 2007). Although TtB extends our understanding of the postural stability assessment, different methods of calculation might affect TtB values and interpretation, thus making comparisons between studies difficult (Haddad *et al.* 2006).

1.2.4.5 TtB model vs. Pendulum model

Paloski and Nicholas (1996) concluded that a measure which assesses the COG in relation to the stability limit is "physiologically more accurate and quantitatively more robust compared to the traditional measures".

Traditional measures do not take into account the boundaries of stability of the body. However, the postural control goal is to maintain the body within the boundaries of the BOS. Therefore, traditional measures do not reflect this goal (van wegen *et al.* 2002). There is a need to calculate another measure that addresses that goal, many studies stressed that the assessment of the postural control has to be performed in relation to the distance of the COG from the boundaries of the feet (Koozekanani *et al.* 1980).

The most commonly used balance control model proposes that there is a steady equilibrium point where the COG is placed close to the BOS. While in TtB; the balance control model is based on the stability margin, which does not account for the sway away of the equilibrium point but it is the sway toward the stability limit (Forth *et al.* 2007). In the pendulum model, the control variable of posture is solely the product of the organism while in the TtB; it is the interaction between the organism, environment and task (Newell 1986 cited in Haibach *et al.* 2007, Riccio 1993). Haibach *et al.* (2007) provided additional evidence that TtB is a postural variable that is regulated instead of maintaining minimal motion around the centre of stability region as in the pendulum model.

1.2.4.6 TtB in the ap and ml directions

As mentioned earlier, TtB is defined as the time estimated for COP or COM to reach the boundary of the BOS if it continues on its trajectory at its instantaneous velocity (Haddad *et al.* 2006). As apparent from the previous definition, the core issue in TtB is the stability boundary or limit which is defined by drawing a rectangle or a polygon around the feet. This stability boundary has two dimensions; ap and ml, therefore, TtB is calculated in both the ap and ml directions. The majority of studies calculate TtB in both directions; however, some studies opt to report TtB as a composite value that includes the two dimensions (Schmid and Conforto 2007). It is a debate whether to report TtB values separately or to combine them in one total value.

For the purposes of this thesis, TtB was calculated using COP. Strategies used to control COP in the ap and ml directions are different due to the differences in the alignment of body segments and muscles. Therefore, forces are being generated at different joints with varying directions (Shumway-Cook and Woollacott 2011). COP in the ap direction is controlled by the ankle dorsiflexors and planterflexors while it is controlled by the hip abductors and adductors in the ml direction (Winter 2005). The previous claim suggests that the COP data acquired from the ap and ml directions might provide different information due to the separate mechanisms controlling them. As mentioned earlier studies of TtB vary in the way they calculate TtB and that refers to the different methodologies used in calculating TtB. The next section aims to clarify why TtB is sometimes reported separately in the ap and ml dimensions or as one two-dimension composite measure. Then the difference between both ways will be explained.

Some studies calculated TtB separately, for example; van Wegen *et al.* (2002) calculated TtB in the ap and ml directions, they measured two groups (young and elderly) while standing double stance during different visual conditions (eyes opened and eyes closed). They concluded that older participants had lower TtB values in both ap and ml directions. TtB was lower in the eyes closed condition in both ap and ml directions while the variability of TtB was not significantly different between the younger and older groups in both ap and ml directions. Comparing TtB to traditional spatial COP measures, the former provides additional information about the differences

that might exist between ap and ml directions, these differences are not revealed using the traditional COP measures (van Wegen *et al.* 2002). An example of the differences between ap and ml directions were shown in van Wegen *et al.* (2002), when COP variability was larger in older participants only in the ap direction while differences in TtB were found between the young and older groups in the ap and ml directions, which means that TtB might help in understanding the ml aspect of postural control. In another study by Hertel *et al.* (2006) TtB was calculated in the ap and ml directions during single -leg standing in a group of young women, the study's aim was to assess the reliability, validity and variability of TtB as compared to the traditional COP measures. Also a study by Hertel and Olmsted-Kramer (2007) showed that TtB in both ap and ml directions was lower in patients with chronic ankle instability as compared to healthy controls. Apart from the previous studies Haddad *et al.* (2006) calculated TtB to the boundary to be contacted first according to its trajectory during double stance. The authors suggested that it is more insightful to calculate TtB to the true boundary of contact unless specific directional control strategies need to be investigated.

On the other hand, some studies did not report separate TtB in the ap and ml, instead they calculated a composite TtB that includes the two dimensions of COP trajectory. This two dimensional stability boundary measure is referred as Virtual Time to contact (VTC) which was originally proposed by Slobounov *et al.* (1997). VTC was found to be lower in older participants during double stance (Slobounov *et al.* 1997). Another study by Slobounov *et al.* (2008) concluded that VTC is a sensitive measure to perform as the controlling variable in maintaining of the upright posture. It is noteworthy that Slobounov *et al.* (2008) raised the differences between their method of calculating VTC and other previous studies that used the Riccio method in TtB calculation like van Wegan *et al.* (2002) and Hertel and Olmsted-Kramer (2007). The concept and the computation method of TtB differs between the Riccio method (1993) and Slobounov *et al.* (1997) in these studies, as the VTC computation method takes into account the acceleration vector in two dimensional stability boundary. According to Haddad *et al.* (2006) the different methodologies used in calculating TtB makes it complicated to interpret and compare different studies.

Moreover, few studies calculated TtB only in one direction, as seen in the study by Forth *et al.* (2007) who defined the stability margin only in the ap direction to calculate the TtB in a sample of 155 young and old healthy participants. Unfortunately Forth *et al.* (2007) did not justify their inclusion of one dimension only of TtB but the authors suggested that a more complete picture could be given with the inclusion of the ml direction.

To conclude, in general the studies that have used the Riccio method in calculating TtB reported two separate measures for TtB in the ap and ml directions while the studies that have used the Slobounov method in calculating TtB reported only one measure for TtB because the two dimensions are already included in the computation process. Those who reported TtB in one dimension did not justify their selection and suggested that the inclusion of the other dimension would have been more informative of the data. Therefore, given that TtB measure in this thesis was calculated using the Riccio method, the exclusion of any of the dimensions could mean that some important aspects of postural control are missed out. In order to have a complete picture of the postural control assessment, the inclusion of the two dimensions ap and ml is necessary. Therefore, TtB measure will be reported separately for both dimensions throughout this thesis.

1.2.4.7 TtB in neurological and musculoskeletal conditions

TtB has been investigated in neurological and musculoskeletal studies mainly to detect postural control deficits that could not be measured using the traditional outcome measures. A study by Hertel and Olmsted-Kramer (2007) examined postural control in single leg stance in participants with and without unilateral chronic ankle instability. Results showed that patients with unilateral ankle instability had bilateral lower TtB values (absolute minimum and mean minimum amplitude) and had less variability of the standard deviation of TtB, which indicate postural control deficits. Only one traditional outcome measure was significantly different than the control group though; the COP velocity. This means that TtB measures were able to detect postural control deficits that were not detected by the traditional measures and hence they are best justified to be investigated in the study presented in this thesis.

1.3 Response time

This section includes a review of the second outcome measure in this study. The use of upper limb response time to assess the sensorimotor function in patients with tennis elbow is established in the tennis elbow literature. In this study; response time was measured in the upper limb of patients with chronic tennis elbow which is similar to the previous studies of Pienimaki *et al.* (1997), Bisset *et al.* (2006) and Bisset *et al.* (2009). Moreover, response time was measured in the lower limb in these patients to investigate whether sensorimotor deficits extend to the lower limb as generalised sensorimotor deficits has been suggested to occur in chronic tennis elbow. The expansion of deficits to areas remote to the site of pathology is one of the characteristics of central sensitisation which is suggested to be part of tennis elbow pathology.

1.3.1 Definition

Response time can be defined as the time interval between a stimulus and the completion of a response, the stimulus could be visual, auditory or proprioceptive while the response could be motor or vocal (Kauranen *et al.* 2000). For the purposes of this review, the stimulus is visual and the response is motor. There are different terminologies used in the literature, response time, reaction time and fractionated reaction time are used interchangeably sometimes which might be confusing. It is important to acknowledge the differences between these terms in order to use the right terminology. Response time is the sum of the reaction time and movement time (Schmidt and Lee 2005). The former is the time between the presentation of a stimulus and the beginning of the response and is usually divided into pre-motor time and motor time (Schmidt and Lee 2005). Premotor time which is also known as processing time is a function of central processing or cognition and it is the time between the stimulus presentation and the movement initiation as identified using an EMG (Etnyre and Kinugasa 2002). Motor time is the process of muscle contraction and it is defined as the time between the initiation of movement and the first behavioural indication of the response initiation (Etnyre and Kinugasa 2002). Movement time is the time from the beginning of the response to the completion of the movement (Chang *et al.* 2009).

As reviewed earlier in this chapter, the studies on sensorimotor deficits in tennis elbow (Pienimaki *et al.* (1997), Bisset *et al.* (2006) and Bisset *et al.* (2009)) used the term reaction time to represent the period between the onset of the stimulus and the completion of the movement. The previously mentioned studies used the sensorimotor interface hand module PEB-1 equipment which actually measures the response time. In the literature, reaction time is measured using the EMG and it is used to represent the premotor time and motor time not movement time (e.g. Kato *et al.* 2004; Fukushi and Ohtsuki 2004; Etnyre and Kinugasa 2002). Therefore, the use of the term reaction time in studies that measure the movement time might be confusing as it is commonly used in studies that investigate the premotor time and motor time. For the purposes of this thesis, the term response time will be used as it is more appropriate in the context of measuring the time between the stimulus and the actual movement. Figure 9 shows the process involved in a response time test to a visual stimulus and the differences between the reaction time and response time.

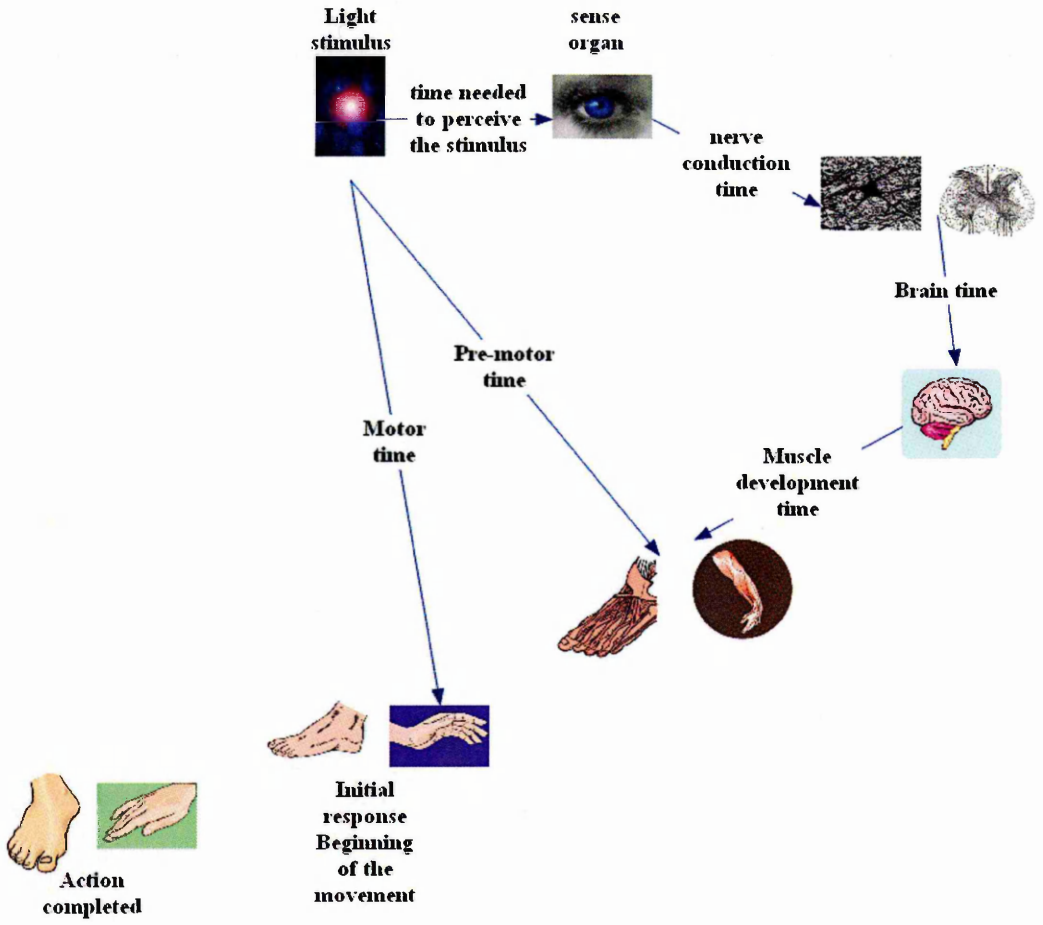

Figure 9: Response time diagram demonstrating the complexity of the mechanism involved.

Response time has been used as a measure of cognitive function and processing speed of the central nervous system (Der and Deary 2006), or sometimes referred to as mental chronometry which means the study of time path of information processing in the nervous system (Carlson and Jensen 1982). It is also used as a measure of motor performance and sensorimotor function (Bisset *et al.* 2009; Bisset *et al.* 2006; Kauranen *et al.* 2000; Pienimaki *et al.* 1997; Kauranen and Vanharanta 1996). It assesses the function of central processing and the coordination of peripheral response, where the role of the central nervous system is to identify the stimulus, recall and choose the appropriate response or initiate a plan to respond, while the peripheral role is to execute a coordinated response (Kauranen *et al.* 2000). Neuromuscular factors that affect the initiation of movement could be that the force generated is not sufficient to produce movement or the range of motion does not allow movement. Sometimes, the inability to

stabilise the body to allow destabilising movements to take place could be another factor that affects initiation of movement. Other factors that might affect the response time include: age, gender, dominant/non-dominant limb, practice and lack of motivation (Shumway-Cook and Woollacott 2011; Kosinki 2009).

1.3.2 Response time measures

There are a number of measures of response time; the commonly used measures are: simple response time, 1-choice response time and 2-choice response time. In simple response time, the target and the response are predefined while in choice response time, there are several targets. In choice response time there is a linear relation between the choice response time and the number of different multiple stimulus response alternatives. This relation is known as Hick's law which implies that choice response time is linearly related to the log of possible stimulus alternatives, this means that the choice response time is linearly related to the amount of information needed to decide upon the different available responses, the time increases constantly when the number of the stimulus-response alternative is doubled. Although Hicks law was first set in the 1950s, it has been used since then. However, new research challenges the assumption of fixed response rate.

1.3.3 Response time in neurological and musculoskeletal conditions

Health professionals are interested in measuring response time in a number of musculoskeletal and neurological conditions because it is a simple way to assess the capability of the nervous system to receive, process, initiate and produce a response to external stimuli (Aley *et al.* 2007). Wrongly; some might think of the response time only in terms of the execution of movement, while it is a chain of processes that starts with receiving the stimuli, identifying it, selecting the appropriate action and finally producing the movement in a timed, sequenced and integrated manner (Aley *et al.* 2007). Unfortunately, response time data alone do not tell the full story of this detailed process especially if there is a problem in the premotor elapse. Therefore, electromyography (EMG) is used to assess the musculoskeletal delay.

Response time has been measured in neurological diseases mainly to assess cognitive and mental processing function. Patients with Parkinson's disease showed increased response time as a result of their bradykineasia and akinesia and it was suggested that this indicate disturbed cerebral processing (Kutukcu *et al.* 1999). Response time has been also measured in some musculoskeletal conditions like carpal tunnel syndrome. Tuhanoglu and Beyazova (2003) found no difference in response time between patients with carpal tunnel syndrome and a control group. However, participants in the control group had also hand pain which could have affected their results. Patients with rheumatoid arthritis also had increased simple response time and movement time when compared to a control group (Kauranen *et al.* 2000). Patients with unilateral chronic ankle instability had longer response time. (Lofvenberg *et al.* 1995).

1.3.4 Response time in Tennis elbow

Response time was the main outcome measure in a number of studies that investigated sensorimotor function in the upper limbs of patients with tennis elbow. The findings of these studies showed bilateral slower response time and decreased speed of movement in patients with unilateral tennis elbow (Pienimaki *et al.* 1997; Bisset *et al.* 2006; Bisset *et al.* 2009). These studies have been discussed in detail under the motor performance impairments: sensorimotor and proprioceptive deficits (see section 1.1.6.2). Although different studies assessed the response time in the upper limb, no study has assessed the response time in the lower limb of patients with tennis elbow to investigate the presence of generalised sensorimotor deficits.

The assessment of response time has been used so far as a predictor of bilateral sensorimotor deficits in patients with tennis elbow (Pienimaki *et al.* 1997; Bisset *et al.* 2006 Bisset *et al.* 2009). Sensorimotor deficits remained after traditional rehabilitation program for tennis elbow; however, traditional rehabilitation for tennis elbow does not include proprioceptive training (Bisset *et al.* 2009). Yet, no study has investigated the effect of sensorimotor training as part of the rehabilitation program in patients with tennis elbow. As reviewed in depth earlier, slower response time and decreased speed of movement indicate a sensorimotor deficit that might be a sign of central sensitisation in patients with tennis elbow. The theories about central sensitisation in tennis elbow are

still in their infancy and in order to engage proprioceptive training in the rehabilitation program for patients with tennis elbow, this should be preceded by research dedicated to investigate the bilateral and generalised sensorimotor deficits in these patients.

1.3.5 Summary

- Balance is one aspect of sensorimotor function that has not been investigated in patients with chronic tennis elbow although generalised sensorimotor deficits have been suggested in these patients. Furthermore, experts in the management of tennis elbow at the Host organisation reported that their patients tend to have poor balance when assessed. Therefore, this study aims to measure balance in patients with chronic tennis elbow to investigate the hypothesis of generalised sensorimotor deficits in these patients.
- Time to boundary is a valid and reliable measure of balance and postural control that has been used in healthy participants and a number of neurological and musculoskeletal conditions. It captures spatial and temporal aspects of postural control; therefore, it is able to detect postural control deficits that are not usually detected by COP traditional measures. Therefore it will be used as an outcome measure for postural control in this study.
- Response time is used to measure motor performance and has been used in healthy participants and a number of neurological and musculoskeletal conditions. It has been also used as the main outcome measure to assess the sensorimotor function of the upper limb in patients with chronic tennis elbow in a number of studies. Findings of these studies have shown bilateral sensorimotor deficits in the upper limbs of patients with chronic tennis elbow.
- One-choice and two-choice response time will be measured in the upper limb of patients with chronic tennis elbow in this study replicating the previous studies in order to compare the findings. One-choice and two-choice response time will be also measured in the lower limb of patients with chronic tennis elbow in this study to look at the extent of generalised central sensitisation suggested in these patients.
- Previous studies that investigated sensorimotor function in chronic tennis elbow used the term "reaction time" instead of "response time". However, the former is commonly used in electromyography studies, therefore, the term response time is more appropriate to be used in the context of this thesis to avoid any confusion.

1.3.6 Summary of the literature review chapter

The aetiology and pathology of tennis elbow are still not clearly understood, what was thought to be an inflammation of the extensor carpi radialis brevis turned out to be not the case, as different studies failed to detect any inflammatory cells in the affected muscles. Therefore, therapeutic approaches used in the management of tennis elbow do not necessarily treat the origin of the problem itself because the exact pathology is not known yet. Instead, the current management of tennis elbow is directed toward the local pathology and it mainly aims to treat the symptoms. For a group of patients, the conservative treatment is not effective where the condition tend to reoccur and develop to be resistive to treatment. The chronicity of tennis elbow that is persistent and resistive to treatment raises concerns about the current methods of treatment. Consequently, it is questionable whether current management of tennis elbow is evidence based. Therefore, one of the objectives of this study is to support the development of new methods for the management of chronic tennis elbow by providing new knowledge in the field of sensorimotor function in these patients.

Accumulating evidence of bilateral sensorimotor deficits and bilateral hyperalgesia in patients with unilateral tennis elbow suggest the involvement of central sensitisation processes which means that chronic tennis elbow is not of a purely musculoskeletal origin as health professionals have suggested for decades. As a result of the findings of neurological involvement; a new integrative theoretical model was proposed by Coombes *et al.* (2009). The model proposed that tennis elbow involves three elements; tendon pathology, sensorimotor impairments and pain system changes. The new model challenges the current management of tennis elbow which only addresses part of the problem and the other factors are being neglected. Neglecting the sensorimotor deficits and pain changes that occur might be responsible for persistent chronic tennis elbow that does not responding to treatment. Therefore, therapeutic approaches should address these changes by, for example, including ways of normalising the central nervous system to overcome the pain system changes. This model is still theoretical and further studies are needed to understand the exact mechanism of tennis elbow pathology. This PhD study aims to contribute to the

development of the new integrative model by providing new knowledge in the field of sensorimotor function in chronic tennis elbow.

Apart from the research findings of bilateral sensorimotor deficits in the upper limb of patients with unilateral tennis elbow, clinical observations of balance problems in patients with tennis elbow were reported by experts in tennis elbow management at the Host organisation, Sheffield. Yet only one study investigated the sensorimotor function of the lower limb and that study investigated the proprioception of the knees not the response time which was investigated in the upper limb in other studies. In order to investigate whether there is a generalised sensorimotor deficit in patients with tennis elbow, sensorimotor function of the lower limb needs to be investigated.

The overall aim of this PhD program was to create a new knowledge in the field of sensorimotor function in patients with chronic tennis elbow by investigating the bilateral and generalised sensorimotor function of the upper limb and lower limb in these patients as compared to healthy participants. Two aspects of sensorimotor function were assessed; response time and balance. The use of response time to assess the sensorimotor function in patients with tennis elbow is well established in the literature. Balance assessment was originally inspired by clinical observation of poor balance in patients with tennis elbow, these clinical observation were reported by experts in the management of tennis elbow at the Host organisation, Sheffield.

1.3.7 Purpose of the research

Following this extensive literature review and having identified the gap in the literature, the aim of the study, questions and hypotheses are presented next.

1.3.7.1 Aim

To investigate if there is generalised sensorimotor deficits in males and females aged between 35 and 65 years diagnosed with chronic tennis elbow by assessing the postural control and response time of the upper and lower limbs as compared to healthy participants.

1.3.7.2 Main question

Is there a generalised sensorimotor deficit in patients with tennis elbow compared to healthy participants?

1.3.7.3 Sub questions

- Is there a postural control deficit in patients with chronic tennis elbow when compared to healthy participants?
- Is there a generalised response time deficit in patients with chronic tennis elbow when compared to healthy participants?

1.3.7.4 General hypothesis

- Null hypothesis: There are no generalised sensorimotor deficits in patients with chronic tennis elbow.
- Experimental hypothesis: Generalised sensorimotor deficits are present in patients with chronic tennis elbow.

1.3.7.5 Balance test hypothesis

- Null hypothesis: There is no difference in balance between patients with tennis elbow and the healthy participants.
- Experimental hypothesis: Patients with tennis elbow are less stable when compared to the healthy participants.

1.3.7.6 Response test hypothesis

- Null hypothesis: There is no generalised response time deficit in patients with chronic tennis elbow when compared to the healthy participants.
- Experimental hypothesis: Patients with tennis elbow have slower response time and decreased speed of movement when compared to the healthy participants.

Chapter 2

Methods

Chapter 2: Methods

This PhD study was carried out as two phases of data collection; the first phase was a normative data collection and the second phase involved patients diagnosed with tennis elbow. Sampling, design, research protocol, ethical consideration and data analysis are presented in this chapter.

2.1 Sampling

2.1.1 Healthy Participants

Twenty two healthy adults participated in the study, 8 males and 14 females, mean age (50.95 years), ranging from (41 to 60 years). Healthy participants were volunteers from the staff at Sheffield Hallam University and friends, demographics of healthy participants are presented in Table 4. Participants completed a screening form (Appendix 1-a) to determine their eligibility to join the study. Participants were excluded if they reported any balance problem, neurological disease, musculoskeletal disease, tennis elbow, non corrected visual problems or if they were taking medications that affected their balance. The study was approved by the research ethics committee in the Faculty of Health and Wellbeing at Sheffield Hallam University.

Demographics of healthy participants (n=22)	
Age	Range 41-60 years, Mean 50.95 years
Sex	8 Males / 14 Females
Dominance of hand	21 Right hand / 1 Left hand
Dominance of foot	20 Right foot / 2 Left foot

Table 4: Demographics for healthy participants

2.1.2 Patients group

Eleven patients participated in the study, 6 males and 5 females, mean age (52.5 years), ranging from (38 to 65 years), a detailed profile for these patients is presented in Table 5. Convenient sampling was used to recruit patients from the orthopaedic out-patients clinic at the Host organisation, Sheffield, UK. The diagnosis was confirmed by an elbow surgeon in the orthopaedic clinic after clinical tests and x-ray. Patients were

included if they had the symptoms for at least 6 months. Participants completed a screening form (Appendix 1-e) to determine their eligibility to join the study. Participants were excluded if they reported any balance problem, neurological disease, musculoskeletal disease, non corrected visual problems or if they were taking medications that affected their balance. NHS ethics approval and clinical governance were cleared prior to the study by the South Yorkshire Research Ethics Committee.

Sex	Age	Chronicity	Unilateral-bilateral	Affected elbow	Resolution of symptoms	pain killers	Physiotherapy	Taping	Aqua puncture	Steroid injection	Due to surgery	Pain	occupational related/sport	Recurren
F	38	6 months	Unilateral	Dominant	No									
M	43	9months	Unilateral	Dominant	No									
M	43	6months	Unilateral	Dominant	No									
M	50	12 months	Unilateral	Dominant	No		√	√				Only flares	PC work/ badminton	
F	51	6 months	Unilateral	Dominant	Yes		√					Occasionally at rest/ gripping/ not severe		
F	57	6 months	Unilateral	Dominant	No		√		√				Professional Tennis	
M	57	8 months	Unilateral	Dominant	Yes				√					
M	57	9months	Unilateral	Dominant	No					√				3rd time ir years
M	57	6 months	Unilateral	Dominant	No									
F	59	3 years	Unilateral	Dominant	No	√					√	Severe	Jewellery maker/ Yuga	
F	65	2 years	Bilateral (done surgery to one elbow and totally recovered)	Both	No	√	√				√	Severe	Golf	

Table 5: Patients profile

2.1.3 Recruitment and consent

Healthy participants were mainly recruited through the intranet of Sheffield Hallam University, poster advert (see Appendix 1-d), word of mouth and snowball technique. All the participants read the participant information sheet before the start of the study and the test was briefly explained to them then they filled the informed consent form. The study was approved by Faculty of Health and Wellbeing Research Ethics Committee at Sheffield Hallam University. (See Appendix 1-b and 1-c for the consent form and the participant information sheet). The recruitment process and the number of participants recruited and completed the study is shown in Figure 10.

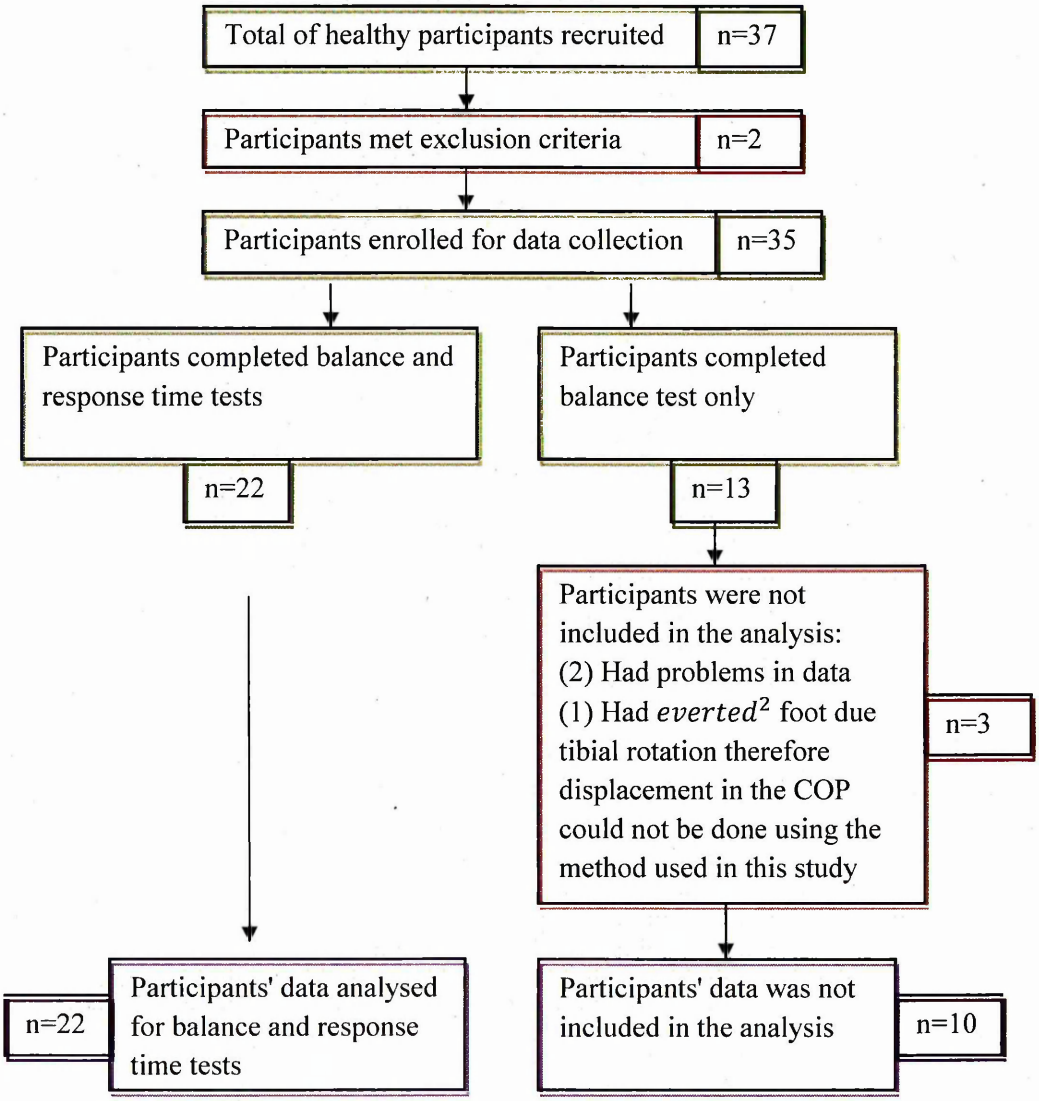

Figure 10: Recruitment and data collection diagram showing the number of healthy participants involved in each stage

In the patients group; potential participants were approached by their orthopaedic surgeon in the orthopaedic out-patients clinic at the Host organisation, who informed them about the study. They were also given an information sheet to take home. The patients were assured that their decision about whether to participate in the study would not affect their treatment in anyway. The contact details of patients who initially agreed to join the study were given to the researcher to liaise with them. Participants were briefed about the study again and asked if they had any questions. Then the participants were given a consent form, they were given time to read and sign and they were informed that they could ask anything they were not sure about. The participants were reminded that they had the right to withdraw from the study at any point and this would not affect their treatment or the service they get in anyway (See Appendix 1-f for the consent form and 1-g, 1-h for the participant information sheet). The recruitment process and the number of patients recruited and completed the study is shown in Figure 11.

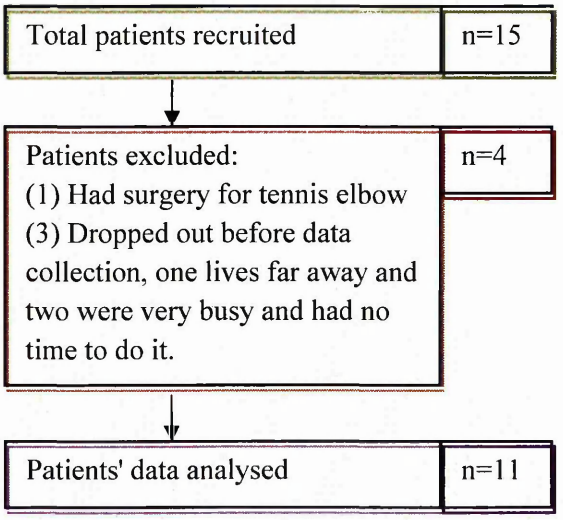

Figure 11: Recruitment and data collection of patients with tennis elbow, showing the number involved in each stage.

[2] The method used to draw the stability boundaries in this study needs the feet to be aligned parallel to the force platform edges, in the case of that participant the tibial rotation resulted in foot eversion (not parallel to the force platform edges).

2.1.4 Ethical Consideration

2.1.4.1 Informed Consent

All participants were asked to read and sign a full informed consent sheet (Appendix 1-b and 1-f) and they had the right to withdraw from the study at anytime without giving any reason. Those who were willing to participate in the study were asked to fill a screening form (Appendix 1-a and 1-e), in order to determine their eligibility to participate in the study.

2.1.4.2 Confidentiality and privacy

No one had access to the study findings except the researcher. Names of participants were saved for recording purposes, while the data processing was anonymous, as different trials were given numbers instead of the participants' names. The data will be stored for 5 years, the electronic data will be preserved in a secured, password protected computer, and the hard copy files will be stored in a locked cabinet at Sheffield Hallam University, the data will be accessed only by the researcher.

2.1.4.3 Information sheet and participants support

All the participants were given sufficient information about the study aims and procedures, as these were contained within the information sheet (Appendix 1-c, 1-g and 1-h), and then participants were informed again before conducting the test. Participants were told that they can ask their questions and all the queries were thoroughly answered. The information sheet included the researcher's contact details (University's address, telephone number and email).

In the patients group, participants were informed that any complaint about the way they have been dealt with during the study or any possible harm they might suffer will be addressed. They were also informed about the normal National Health Service Complaints mechanisms in case they wish to complain, or have any concerns about any aspect of the way they have been approached during this study. The contact address of Patient Advice and Liaison Service could be found at the end of the participant information sheet in case they needed further information or independent advice.

2.1.4.4 Reimbursement and benefits

Participants in the patients group were offered 5 pounds as a reimbursement for the car parking expenses and a refreshment.

2.2 Research design

This study used a quasi-experimental repeated measures design. One of the issues in repeated measures design is the learning effect as the test progresses. This can be a problem because the performance of a participant can change over the course of the experiment. Therefore, habituation trials were carried out to minimise the learning effect. It is also likely that participants become bored or fatigued from the repetition. In this study participants were given short breaks between balance trials and response time trials to avoid fatigue.

In the balance test, there were two dependent variables (TtBap and TtBml) and three independent variables (vision, dominance of foot and group). Vision and dominance of foot were within participants variables and group as between participants variable. For the response time test, there were four dependent variables (1-choice response time and speed of movement, 2-choice response time and speed of movement) and two independent variables (upper/lower limb and dominance of hand/foot).

2.3 Sample size

Sample size is very important to be determined prior to the start of the research, bearing in mind the available resources, time constraints and ethical considerations (Carter *et al.* 2011). For the purposes of this study, the sample size for the healthy participants was determined according to the sample size used in previous similar studies see Table 6. Therefore, the sample size was determined to be 50 participants. However, in regard to the patients group, the sample size was discussed with the clinicians at the orthopaedic department at the Host organisation. After reviewing the number of patients obtained in previous similar studies, it was clear that a large sample size of patients like what has been used in Bisset *et al.* (2009) could have been very difficult to obtain given the referral rate and number of patients over the past years.

Therefore, the sample size for the patients group in this study was estimated according to the number of patients of chronic tennis elbow referred to the Host organisation over the previous years and the aim was to recruit 50 patients over a year.

Study	Sample size	
	Healthy participants	Patients with chronic tennis elbow
Pienimakie *et al.* (1997)	32	32
Bisset *et al.* (2006)	40	40
Bisset *et al.* (2009)	198	40

Table 6: Sample sizes in similar studies

2.4 Research protocol

The study consisted of two tests; balance and response time. The data collection for the healthy participants (first phase) took place in the Biomechanics lab and the Strength and Performance lab at Sheffield Hallam University. The data collection for patients with tennis elbow (second phase) took place in the Orthopaedic department at the Host organisation. The same protocol was used for both groups. The protocol is explained in the following sections.

2.4.1 Balance

Balance was the first test in the study. A brief introduction to the methods and tools used to assess balance is presented in the following section.

2.4.1.1 Instruments

Ragnarsdottir (1996), reported two types of assessment; functional and physiological. Functional assessment is commonly used by health professionals and can be simply done by performing any function like single leg standing; it is simple and usually does not involve expensive equipment (Brown and Hare 2001; Ragnarsdottir 1996). Physiological assessment measures the COP and COM using special tools that are used for different purposes, some are available commercially and some only used in research laboratories. For the purposes of this work, physiological measures were assessed during single leg standing; a functional test that is commonly used by health

professionals in the assessment and treatment of different musculoskeletal and neurological conditions.

2.4.1.2 Experimental set up

A Kistler force platform embedded in the ground connected to a computer for data acquisition was used for the healthy participants and a portable Kistler force platform connected to a laptop was used for patients with tennis elbow. Three ground reaction forces were recorded (Fx, Fy and Fz) in the medio-lateral (ml), anterio-posterior (ap) and vertical directions respectively. The COP distances were also recorded in the ml and ap directions (Ax, Ay). A sampling rate of 100 Hz was used and the data was filtered using a 19 tap Hamming windowed finite-impulse-response low-pass digital filter with a 10 Hz cut-off frequency implemented as an Excel macro

Figure 12: Kistler portable force platform (http://www.kmu.edu.tw/~sportsmed/Guo/English/lib_1.htm).

Force platforms seem to be the most suitable balance measurement equipment to be used in clinical situations whether for evaluation or for monitoring progress because health professionals can get a real time display and detect small changes in the patients' ability to maintain balance (Brown and Hare 2001).

2.4.1.3 Balance test protocol

Before the test was carried out, participants were given the participant information sheet and the consent form to sign. Then they were given the instructions for the study and any questions or concerns were answered and discussed thoroughly. Both the right and left foot were tested in two visual conditions (closed and open). The

consequence of testing the foot and visual condition was randomised by asking the participants to choose two envelopes (one white and one brown out of four envelopes) inside the white envelopes there was two cards for the foot to be tested (right and left), while inside the brown envelopes there was two cards for the visual condition (eyes open and eyes closed).

Participants were asked to take off their shoes and socks then they were asked to stand bare foot on the force platform which was covered with a paper. They were asked to put their foot as central as possible over the force platform then a trace of the participant's footprint was taken by drawing a line around their foot over the paper. Each foot trace was marked with a different colour and participants were asked to stand over that footprint trace during all the trials to ensure a consistent foot placement. Participants were asked to step onto the force platform and they were instructed to stand on one leg. In the eyes opened condition participants were asked to look in front of them at a visual target (black x sign) placed on a screen one meter away from the force platform. While in the eyes closed condition, they were asked to close their eyes and maintain their head in a position and orientation as if they were looking at the visual target. They were instructed that once they are balanced on one leg they have to give a verbal signal in order to start the data collection. They were asked to stand as quite as possible with their arms beside their bodies but they were allowed to move their arms, head and trunk if needed to regain their balance. The trial was repeated if the eyes were opened in the eyes closed condition or if the foot placement on the trace was changed. This included touching the ground or the force platform with the raised leg.

The instructions for the eyes opened condition was: "Look at the black x sign in front of you and maintain your head in that position, stand as quiet as possible, however, if you feel like you are going to lose your balance or fall, it is okay to try to regain your balance by moving your head, truck and arms but make sure that the your foot is always over the footprint. If you step or fall the trial will be repeated. Please give me a sign when you are ready so I could start the data collection". The instructions for the eyes closed were the same as the eyes opened condition except that they were asked to: "close your eyes while maintain your head in the centre as if you are looking at the black x sign in front of you".

The participants were asked to stand on one leg for at least 10 seconds, however they were instructed that they could stand for longer if they can as the Bioware software was programmed to record the trial for one minute. The researcher remained silent during the test so as not to distract the participants and a chair was placed next to the force platform so they could rest between trials. Figure 13 shows a volunteer during the balance test.

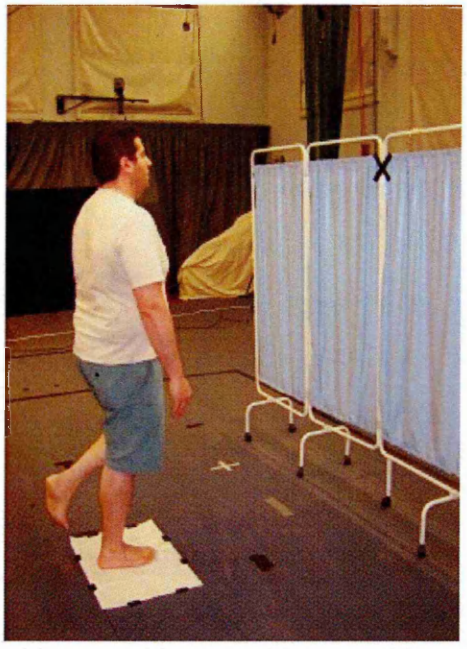

Figure 13: Balance test, single leg standing in front of a screen. Standing over the built-in force platform. (Biomechanics lab/ Sheffield Hallam University).

Trials were repeated in the following instances: raised leg touched the platform, the ground or the other leg, the stance (tested) foot moved from the trace drawn over the platform, lifting of the heel or the forefoot in the stance leg, falling, opening of the eyes in the eyes closed condition and touching the chair. Participants were allowed to try to regain their balance if disturbed, in this case the trial was counted unless one of the previous mentioned situations occur. The participants performed twelve acceptable trials in total, six in the eyes opened condition and six in the eyes closed condition as follows: right foot/ eyes opened (x3), right foot/ eyes closed (x3), left foot/ eyes opened (x3) and left foot/ eyes closed (x3). The time of the test was 10 seconds.

2.4.1.4 Balance measures

The balance measure in this study was TtB. The Bioware software of the force platform measures the COP displacement in mm in the ap and ml directions (Ax and Ay). The COP displacement was used to calculate TtB.

2.4.1.5 Methods of TtB calculation

There are two common methodologies to calculate the TtB: the TtBs (Slobounov *et al.* 1997) and the TtBr (Riccio 1993), the latter method was used in this study. There are two main differences between both methods. Firstly, TtBs is calculated from the average of the TtB series so all the COP data points is used in calculation, while the TtBr is the average of the minima which only represent the COP data points when the individual was less stable. Secondly, TtBs uses acceleration information which is not used in the TtBr method. Therefore, the TtBs is considered to be more representative of the trial; however the TtBs is more sensitive to filtering because it uses the acceleration in calculation, so TtBr might be more robust during the dynamic sway movements (Haddad *et al.* 2006). Although the participants were asked to stand still during the study, dynamic sway was observed in the eyes closed condition. The Riccio method was used in this study, although it might not be representative for the whole trial but it captures the points where the balance is most threatened, therefore, identifying any balance deficit which is the aim of this study.

2.4.1.6 Issues to consider in calculating TTB

- Assessing the base of support or stability boundary

To calculate the TtB, the boundaries of stability have to be defined first. Simple rectangles or polygon could be drawn around the foot. The multi-segment polygon or trapezoid might be more representative because there are no spaces between the foot borders and the stability boundaries as seen in the rectangle. However, because this study involved only single leg standing the small spaces left in the rectangle can be neglected (Haddad *et al.* 2006). Moreover, drawing a simple rectangle around the foot is much easier and straight forward in the data analysis therefore; it was used in this study (figure 14).

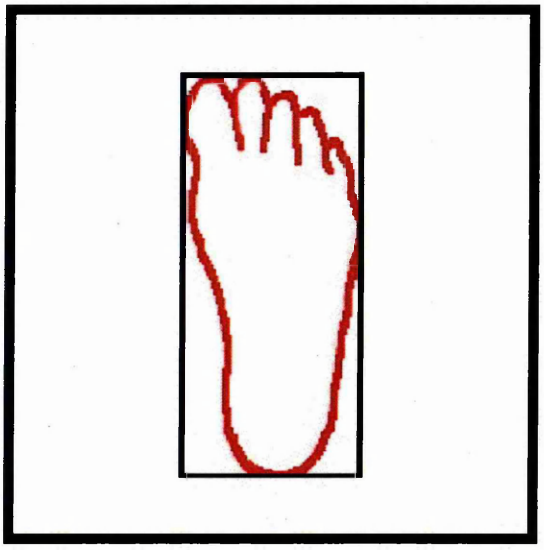

Figure 14: Example of the rectangle stability boundary drawn around a foot trace

- Using COP or COM.

Both the COP and the COM can be used in calculating TtB. Whether COP or COM is used, it should be born in mind the difference in interpretation of the postural stability because COP and COM do not represent the same thing. COM might be easier to interpret due to the fact that if the COM is out of the BOS, the individual will fall unless the balance is recovered by stepping. On the other hand, COP does not have a direct consequence like COM which makes it harder to explain. However, using COP in calculating the TtB might be more relevant because the COP is the controlling variable. It was noticed also that TtB was longer when using COM because its velocity, acceleration and excursion is smaller than COP (Haddad *et al.* 2006). For the purposes of this study, COP was used in calculating TtB because it is the controlling variable. Also COP was also recommended by Haddad *et al.* (2006) to be used in studies aim to separate clinical populations, which ties well with the aim of the study in investigating sensorimotor differences between patients with tennis elbow and healthy participants.

- Sampling rate

Different sampling rates could be found in the literature because they are directly related to the number of data points recorded. The sampling rate used in this study was 100 Hz which was also used by Haddad *et al.* (2006) and van Wegen *et al.* (2002); both studies had similar conditions and purposes to this study.

- Filter cut-off frequency

Cut-off frequencies between 3Hz and 12Hz are usually used in TtB studies (Haddad *et al.* 2006). The filtering affects the TtB more in quiet stance rather than active sway because of the nature of the COP and COM movements in quiet stance (low amplitude and high frequency) (Haddad *et al.* 2006). The cut-off used in this study was 10 Hz which was used by van Wegen *et al.* (2002).

2.4.1.7 TtB calculation in this study using the Riccio method

TtB calculation starts from the foot trace drawn on the paper that was placed over the force platform. On the paper of the foot trace, the distances to stability boundaries are measured. Then these distances are copied into Excel sheets along with the data exported from the Bioware software (force platform software). The TtB ap and ml were calculated using special macros and formulas. A detailed step by step TtB calculation is explained below.

The foot anatomical references were defined on the paper; the toes anteriorly, the heel posteriorly, the 1st and the 5th metatarsal heads medially and laterally respectively (used by Haddad *et al.* 2006). Then the stability boundaries were defined using the previous anatomical landmarks. As explained earlier, the boundaries could be defined either by a rectangle or a trapezoid surrounding the area around the foot. For the purposes of this study; the boundaries were defined as a rectangle and the feet were parallel to the edges of the force platform (used by Hertel *et al.* 2006 and Haddad *et al.* 2006). Four distances to boundary were measured from the centre of the force platform (centre of the paper) to each stability boundary; anterio-posterior (-ap), (+ap) and medio-lateral (-ml) (+ml), See Figure 15.

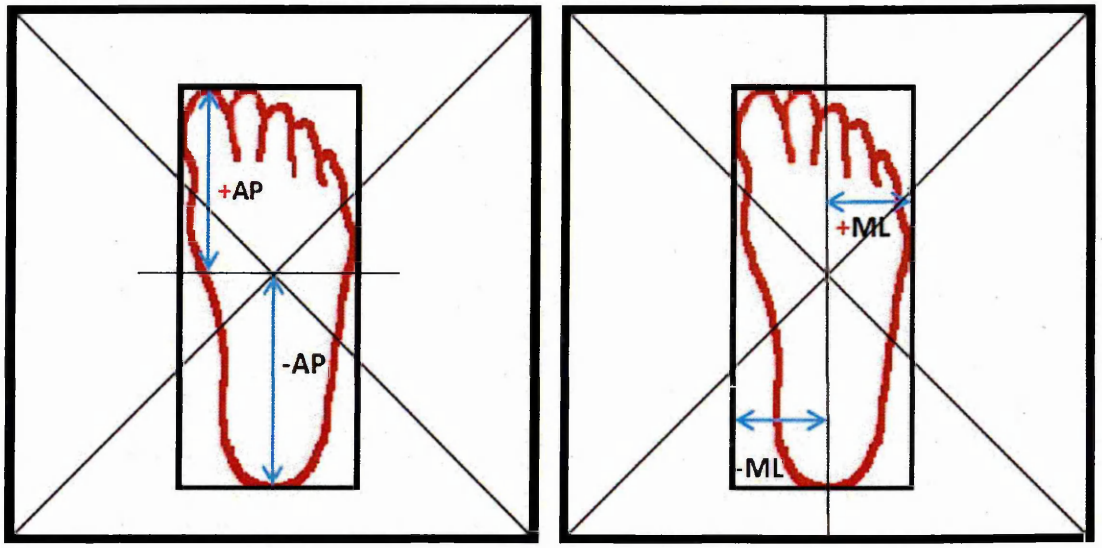

Figure 15: The four distances (+AP, -AP, +ML and –ML) measured to calculate TtB.

The data were exported from the Bioware and opened in Excel. The distance values measured previously were copied into Excel. The COP velocity was calculated using the following equation:

$$\mathrm{vel}_{COP} = \frac{\mathrm{d}_{COP}}{0.01} \qquad \textbf{(Equation 2.1)}$$

Where vel_{COP} is the velocity of the COP and d_{COP} is the distance of the COP.

Then the TtB ap and ml were calculated using the following equation:

$$\mathrm{TtB} = \frac{\mathrm{d}_{boundary}}{\mathrm{vel}_{COP}} \qquad \textbf{(Equation 2.2)}$$

Where $\mathrm{d}_{boundary}$ is the distance to boundary and vel_{COP} is the velocity of the COP.

The TtB values were sorted in an ascending manner, then the first ten minimum TtB values were used in the final averaging. Figure 16 shows an example of TtB data where the valleys represent the minimum TtB values or the minima.

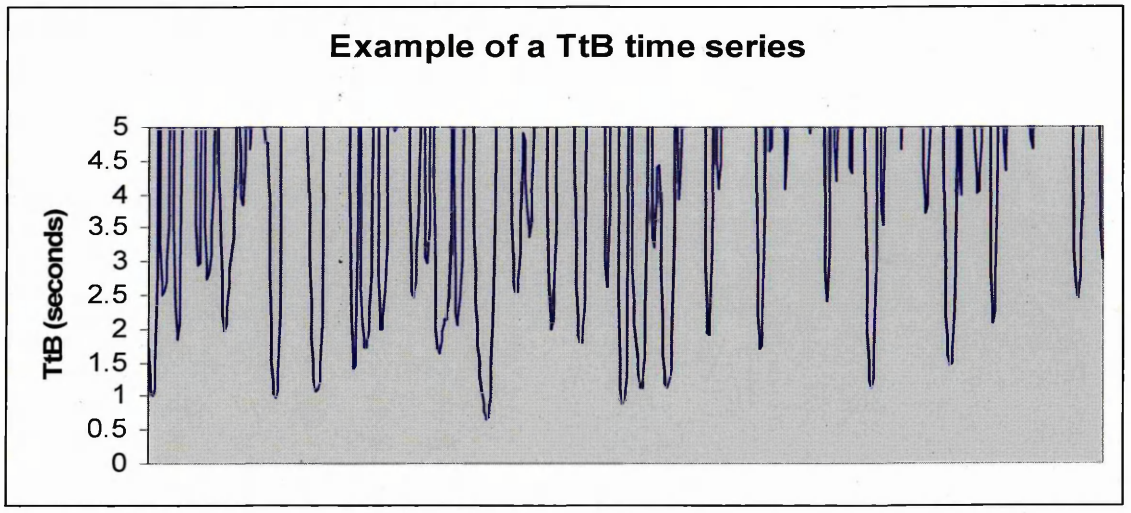

Figure 16: Example of TtB time series (The TtB values in the valleys represent the minima which were used in the final averaging).

2.4.2 Response Time

Response time was the second test in the study. The instrument, outcome measures and protocol are explained next.

2.4.2.1 Instruments:

Response time has been investigated in patients with tennis elbow previously but only in the upper limbs (Pienimaki *et al.* 1997; Bisset *et al.* 2006; Bisset *et al.* 2009). These studies used the sensorimotor interface hand module of the basic elements of performance system (BEP-1) supplied by the Human performance measurement, Inc. Arlington, TX USA. The response time equipment used in this study was designed and made by the Centre for Sports Engineering Research at Sheffield Hallam University and it is very similar to the equipment used in other studies. However, it is simpler, cheaper and it can be used to measure response time in both the upper and lower limbs. Figure 17 shows the response time equipment used in this study while Figure 18 and Figure 19 show the sensorimotor interface hand (BEP-1) and foot (BEP-2) modules that are commercially available.

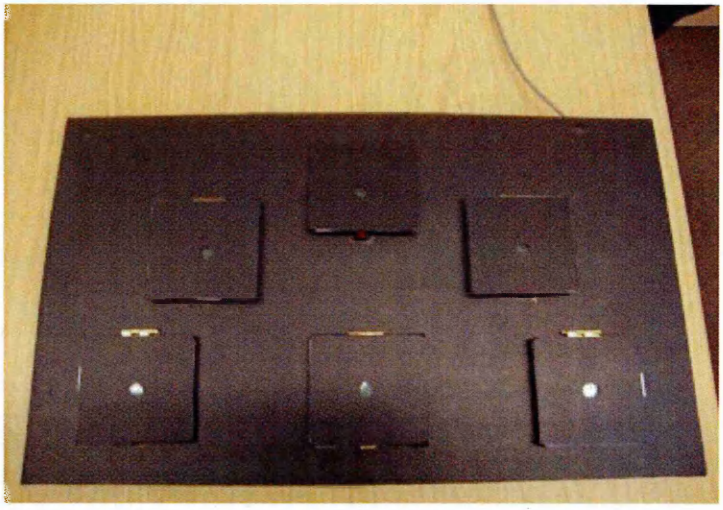

Figure 17: Response time equipment used in this study (designed and made by Centre for Sports Engineering Research, Sheffield Hallam University).

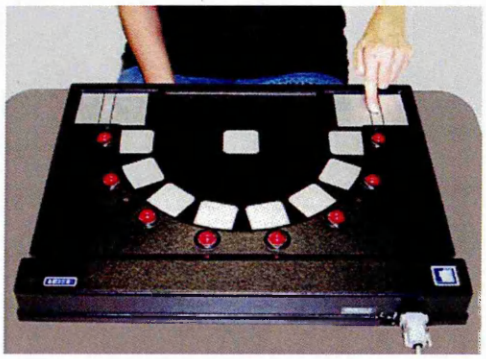

Figure 18: BEP-1 Hand module that was used in previous studies. (http://home.flash.net/~hpm//pages/HPM.products/BEP1.html)

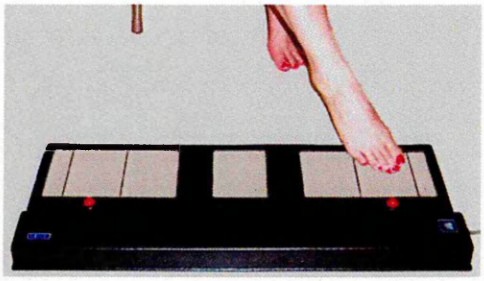

Figure 19: BEP-2 Foot module never used in patients with tennis elbow. (http://home.flash.net/~hpm//pages/HPM.products/BEP2.html)

The response time equipment used in this study was designed based on the BEP-1 and BEP-2 but there are some differences between the equipments. The first difference is the number of pads; instead of 8 pads in the BEP-1 there are 5 pads in the response time equipment used in this study. This is because the BEP-1 is designed to measure up to 8-choice response time while this study only studied 1-choice and 2-choice response time so the other pads were not necessary. The other difference is the location of pads; in order to accommodate the response time equipment used in this study to assess response time in the feet; two pads were located horizontally at the lower end of the equipment just like the orientation of the pads in the BEP-2. The size and location of the lights also vary between the two equipments; the lights in the equipment used in this study are smaller and located under the pads while they are larger and located above the pads in the other equipment. Dimensions for the BEP-1 are 58×46×8 cm while the equipment used in this study dimensions are 48×30×3 cm.

2.4.2.2 Response time measures

Two outcome measures were used to measure the response time; both were assessed in previous similar studies. These are: 1-choice response time and corresponding speed of movement and 2-choice response time and corresponding speed of movement.

2.4.2.3 Response time test protocol

Both hands and feet were tested. The order of the limb to be tested was randomised by asking the participant to select two envelopes out of four (two brown envelopes contain two cards for arms and legs and two white envelopes contain two cards for right and left). The participant was asked to place the limb to be tested on the central pad (start). Then the participant was asked to move the hand or foot toward the light. For the hand test, the equipment was placed over a table and the participant was sitting in a comfortable back supported seat. For the foot test, the equipment was placed on the ground and the participant was sitting on a comfortable back supported seat. The protocol and outcome measures used for reaction time were derived from similar previous studies (Pieneimakie *et al.* 1997; Bisset *et al.* 2006; Bisset *et al.* 2009).

To assess the 1-choice response time participants were instructed to lift the tested hand/ foot immediately after the light stimulus appeared and to move it as quickly as possible to the pad of the activated light. Two different measures were obtained from each trial: (a) 1-choice response time, expressed in seconds, is the time between the appearance of a light stimulus and the hand/foot lifting from the centre plate; (b) movement speed, expressed in cm/s, is determined as the distance between the centre plate and the target plate (distance 16 cm) divided by the time needed for the performance of the movement. The participants performed five trials. For the 2-choice response time participants performed the same test in the 1-choice response time but there were two possible activated light time participants knew beforehand which light will be on. While for the 2-choice response time participants were told that for the upper limb it could be either pad 2 or pad 4 that will be lit. For the lower limb either pad 1 or pad 5 was activated. In both the upper and lower limb conditions, participants were not aware of which pad would be activated in any particular trial. The randomisation for the order of 2-choice response time was done manually to ensure 3 trials for each pad target. For example the order of targets for the 2choice response time in the upper limb could be: 2,2,4,2,4,4 or 2,4,2,4,2,4 etc… Figure 20 shows the order of the pads for the upper and lower limbs.

Participants completed three habituation trials in each condition to familiarise them with the test procedure and minimise the learning effect associated with repeated measures design. During data collection any erroneous trials were repeated. Examples of errors that occurred include premature anticipation of the stimulus. Participants waited for 4-6 seconds till the light was on. The instructions given to participants in the 1-choice RT test were:" Put your hand/foot on the central pad, the light will come from this pad (the researcher points to the target pad), when the light is on, remove your hand/foot of the central plate and hit that pad (the researcher points to the target pad) as quickly as possible, try not to slide your hand/foot when you move it from the central pad to the target pad". The instructions given for the 2-choice RT were the same except that two pads were identified instead of one.

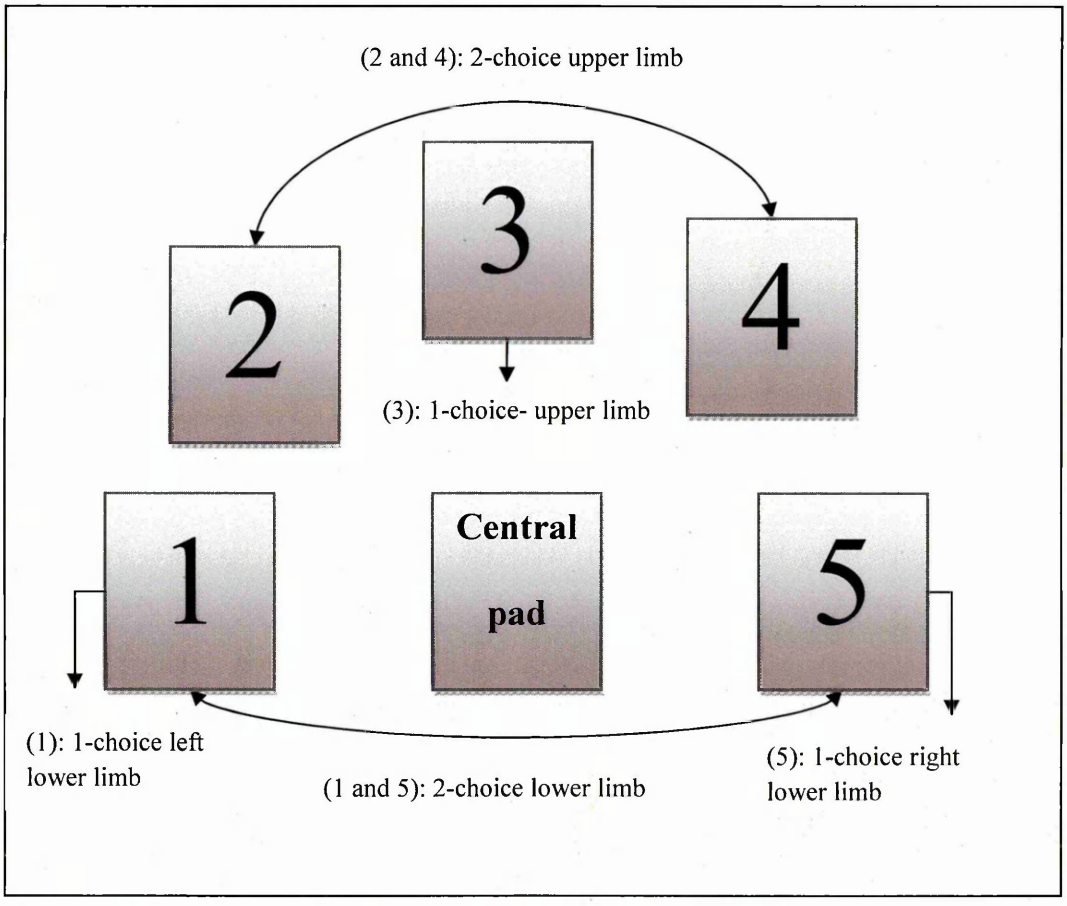

Figure 20: Basic diagram of the response time equipment showing the placement of pads in the 1-choice and 2-choice response time measures.

2.5 Data processing and analysis

Balance data was first exported from the Bioware software to Excel sheets and filtered using the low filter pass of 10 Hz. Then TtB was calculated using equations as discussed in detail under the section of balance measures. The TtB values were analysed using SPSS. Response time data was copied from the response time software into Excel, where the average of best three results was calculated for the 1-choice response time and the average of the best two results was calculated for the 2-choice response time. Then the values of 1-choice and 2-choice response time were analysed using SPSS.

Descriptive statistics were calculated for the balance and response time data and mixed design ANOVA was used to analyse the data. Parametric assumptions of normality and homogeneity of variance were checked before running the analysis.

Chapter 3

Test-retest reliability of measures

Chapter 3: Test-retest reliability of measures

3.1 Introduction

Reliability refers to the ability of a test or measure to produce consistent results; sometimes it is used interchangeably with the term reproducibility (Field 2009; Hopkins 2000). There are different types of reliability; therefore, the quantification of reliability varies according to the aim and design of the study. Methods of reliability calculations are numerous, reliability estimates calculated using different formulas will yield different results even for the same set of data. Therefore, it is crucial to justify the suitability of the chosen reliability analysis in order to avoid false inferences (Weir 2005). Two reliability studies were carried out: the aim of these studies was to assess the test retest reliability of time to boundary, response time and speed of movement. In test retest reliability studies the aim is to investigate the ability of the measure to produce consistent results when the same participants are tested at different points in time (Field 2009).

Among the different available estimates for test retest reliability, the following remain the most commonly used ones in physiotherapy: hypothesis tests of bias (e.g. ANOVA), correlation coefficients (e.g. ICC), Bland and Altman plots 95% limits of agreement and standard error of measurement (Bruton *et al.* 2000). None of these estimates is sufficient alone to give enough information about reliability. Therefore, it is recommended to combine different types together in order to draw useful conclusions about reliability (Bruton *et al.* 2000; Weir 2005). According to the recommendations made by Hopkins *et al.* (2009), the following reliability estimates were used in this study: the hypothesis tests of bias, standard error of measurement and the intraclass correlation coefficient (ICC).

The Bland and Altman plots 95% limits of agreement was not calculated in this study as it has been increasingly criticised for being used as a reliability index. It was originally developed to look at the agreement between two different techniques used to measure the same variable rather than an estimate of reliability (Weir 2005). Moreover,

a recent article by Hopkins *et al.* (2009), on progressive statistics for studies in sports medicine and exercise science, recommended avoiding the limits of agreement as a statistical measure of reliability as they do not provide further clinical or theoretical value.

The calculation and interpretation of reliability estimates are based on an understanding of the sources of error. There are two main types of error; systematic error and random error. The former include learning effect and fatigue for example, where a unidirectional change in scores is expected to be seen on repeated testing whether as an improvement or deterioration (Weir 2005; Bruton *et al.* 2000). Whereas the random error is associated with normal biological variability and chance factors like alertness of the participants and attentiveness by the tester (Weir 2005; Bruton *et al.* 2000). Random error is the error of interest in reliability estimates while the inclusion or exclusion of systematic error in reliability estimates is debatable (Weir 2005).

3.2 Study-1: test-retest reliability of time to boundary

3.2.1 Methods

3.2.1.1 Participants

Six healthy participants, 3 females and 3 males (age 48.5±7.7 years) were recruited. All participants were members of the staff at Sheffield Hallam University except one who was recruited from the local community. Participants completed a screening form to check that they were free from any neurological or musculoskeletal conditions or taking any medication that could affect their balance. All signed a consent form and were given verbal and written information about the study. Ethics was approved by the Sheffield Hallam University Ethics Committee.

3.2.1.2 Experimental procedure

Participants performed single leg standing for 10 seconds in two visual conditions (eyes closed and eyes opened) and for the right and left foot. For each condition three trials were recorded. Test and retest trials were carried out over two sessions. Sessions were separated by two weeks period and the retest was performed at

the same time of the day as the first test. The data for all the participants were collected by the researcher. The protocol used for data collection here was the same as the one described in the methods chapter for the main study.

3.3 Study-2: test-retest reliability of response time and speed of movement

3.3.1 Methods

3.3.1.1 Participants

Seven healthy participants, 5 females and 2 males (age 46.8±5.3 years) were recruited. Participants completed a screening form to check that they were free from any neurological or musculoskeletal conditions that could affect their sensorimotor function. All signed a consent form and were given verbal and written information about the study. Two participants were members of the staff at Sheffield Hallam University and the rest of participants were recruited from the local community. Ethics was approved by the Sheffield Hallam University Ethics Committee.

3.3.1.2 Experimental procedure

The reliability study consisted of two sessions separated by 30 minutes rest time. Response time and speed of movement were measured in the upper and lower limb using equipment designed by the Centre for Sports Engineering Research at Sheffield Hallam University[3].The data for all the participants were collected by the researcher. The protocol used for data collection here was the same as the one described in the methods chapter for the main study.

3.4 Data analysis and results

Given that there were a large number of variables, the TtB measures for dominant foot and non dominant foot were pooled together. Similarly, the 1-choice RT and SM measures for dominant and non dominant limb were pooled together while for

[3] Refer to the methods chapter for details and full description of the equipment used in this study.

the 2-choice RT and SM, the dominant and non dominant limb for the same side and other side targets were pooled together. Pooling the data together reduced the number of variables as reliability estimates were calculated for a total of 12 measures instead of 32. This would make it easier for interpretation. Pooling the measures together did not change the data as no calculations were made. (See Figure 21)

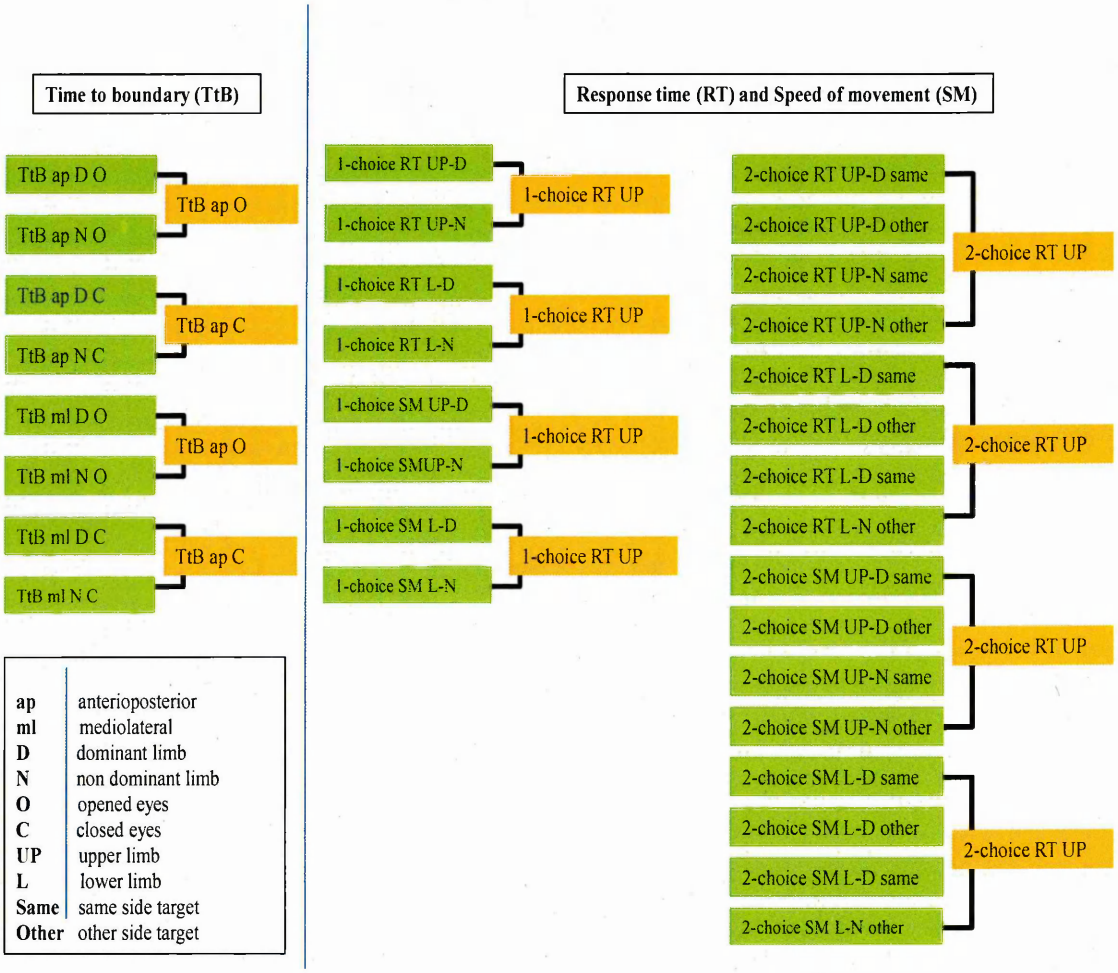

Figure 21: Outcome measures that were tested for reliability

Microsoft Office Excel 2007 was used to calculate the reliability estimates. Next, the results of three reliability estimates calculated for the TtB, RT and SM are presented and followed by an overall discussion of the findings.

3.4.1 Hypothesis tests of bias- ANOVA

The change in the mean between trials was calculated in order to identify the presence of systematic error. For all the tested measures in this study, the results of repeated measures ANOVA[4] showed a non significant effect of the trials which indicates that there is no statistically significant systematic error in the data at $p = 0.05$. Non significant p values are presented in Table 4.

Outcome measure	*p values*
TtB ap C	0.878
TtB ap O	0.794
TtB ml C	0.691
TtB ml O	0.150
1-choice RT up	0.179
1-choice RT L	0.778
1-choice SM up	0.999
1-choice SM L	0.445
2-choice RT up	0.515
2-choice RT L	0.356
2-choice SM up	0.203
2-choice SM L	0.760

Table 7: p values of ANOVA

3.4.2 Intraclass correlation coefficient (ICC)

The ICC is a relative measure of reliability and can be simply defined as the ratio between the between-subject variability and between-subject variability + error. Variances are derived from the results of single factor repeated measures ANOVA and the final ICC value is unitless and falls between 0 and 1, where higher ICC values indicate better reliability. The ICC might look simple; it is not straightforward though, because there are different equations available to calculate the ICC. Shrout and Fleiss (1979) reported six different equations for ICC and when to use them. The selection of the appropriate ICC needs to address four issues as suggested by Weir (2005). According to Weir's suggestions, a 3,k, 2-way, fixed-model was used to calculate the ICC in this study. (See Table 5 for details of why this model was selected). The following equation was used to calculate the ICC in this study:

[4] Parametric assumptions were checked before conducting ANOVA. The level of data was ratio and the normality was checked using Kolmogorove-Smirnov test and it was not significant, which means that the data was normally distributed.

$$ICC(3,k) = \frac{MS_S - MS_E}{M_S}$$ **(Equation 3.1)**

Where M_S is the subjects mean square and M_E error mean square. This equation is adopted from Shrout and Fleiss (1979).

Issues to be considered before ICC selection	**Justification in regard to this study**
1-or **2-way model**	To be used in test retest study where trials are crossed with participants
Fixed or random effect model	To be used when the aim of the study is to establish the reliability of a test before using it in the main larger study and no generalisation will be made beyond this study.
Include or **exclude systematic error**	Model 3 only considers random error.
Single or **mean score**	Average scores were used.

Table 8: Issues to be considered when choosing the ICC.

In order to interpret the ICC values, the rule is simple, the higher the ICC value, the better is the reliability. Some indices have been proposed indicating good or poor reliability. Nevertheless, these indices vary which makes it difficult to decide which one to adopt. Some authors prefer not to link their reliability estimates to any index and let the reader decide on the practical significance instead (Weir 2005). However, according to Fleiss (1986), an ICC > 0.75 indicates excellent reliability while if the ICC ranged from 0.40-0.75 this indicates fair to good reliability and if the ICC < 0.40 this indicates poor reliability. Given that the ICC (3,k) used in this study was adopted from Shrout and Fleiss (1979), the index of Fleiss (1986) will be used as a guide to interpret the ICC.

3.4.3 Standard error of measurement[5]

The standard error of measurement, or sometimes known as typical error is an estimate of absolute reliability that quantifies the precision of the individual scores in the variable (Hopkins 2000; Weir 2005). Unlike the ICC it has the same units as the measured outcome and it is independent from the sample it was obtained. The sources of variation shown by the standard error of measurement could be biological or technical noise from the equipment (Hopkins 2000). The smaller the number of standard

[5] Sometimes the abbreviation SEM is used, however, it is recommended not to use it as this might be confused with the standard error of mean (Hopkins *et al.* 2009).

error, the better the measure as this indicates less random error or noise in the measure. The standard error of measurement and the confidence intervals were calculated using the following equations:

$$\text{Standard error of measurement} = SD\sqrt{1 - ICC} \qquad \textbf{(Equation 3.2)}$$

Where SD is the standard deviation of all the scores and ICC is the intraclass correlation.

$$CI = \overline{X} \pm (1.96 \times \text{Standard error}) \qquad \textbf{(Equation 3.3)}$$

Where $\overline{X}$ is the total mean.

The reliability estimates for the TtB, RT and SM are presented in Table 6.

Outcome measure	ICC	Standard error of measurement[6]	Confidence Intervals	
			Lower boundary	Upper boundary
TtB ap C	0.85	0.122	0.416	0.895
TtB ap O	0.85	0.374	1.323	2.789
TtB ml C	0.85	0.032	0.138	0.263
TtB ml O	0.94	0.067	0.442	0.705
1-choice RT up	0.53	0.029	0.208	0.321
1-choice RT L	0.92	0.014	0.259	0.314
1-choice SM up	0.94	0.079	0.564	0.874
1-choice SM L	0.95	0.050	0.624	0.820
2-choice RT up	0.60	0.036	0.265	0.407
2-choice RT L	0.80	0.041	0.284	0.444
2-choice SM up	0.89	0.122	0.432	0.91
2-choice SM L	0.70	0.184	0.251	0.972

Table 9: Reliability estimates for TtB, RT and SM.

3.5 Discussion

The aim of the two reliability studies was to investigate the test retest reliability of the TtB, RT and SM in healthy participants in order to use these measures with confidence in the main study of this PhD program. Therefore, the results of the reliability estimates presented here are not to be generalised beyond the confines of this research.

[6] The units for the standard error of measurement are: seconds (s) for the TtB, RT and meter/seconds (m/s) for the SM.

Before discussing the findings of the reliability estimates of postural control and response time measures, it is important to bear in mind the inherent variability in the motor control system of healthy individuals (Hertel *et al.* 2006). This variability is more evident in tasks that are not challenging enough to participants as this will leave them with more options to adjust their posture (Hertel *et al.* 2006). This explains why reliability estimates might not be very high in measures that involve human movement.

The non significant *p* values shown in the results of ANOVA indicate that there was no systematic change in the mean of the measure between consecutive trials. These systematic changes are predictable and unidirectional (either improvement or deterioration of performance) these include learning effect, fatigue, soreness and motivation (Bruton *et al.* 2000; Hopkins 2000). The elimination of these sources of systematic bias was addressed in the design of the protocol of this study. Familiarisation trials were used to control the learning effect expected as a result of repeated testing. Participants were asked to practise every test before the start of data collection. Allowing participants to practise before the data collection is important as they are likely to do better in their second trial than their first one (Bruton *et al.* 2000). Thus, familiarisation would make their performance reach a plateau, consequently reducing sources of error that might arise from learning, training or other order-dependent effects. To overcome the fatigue and soreness associated with repeated testing, rest periods of two minutes were given between trials in both studies and participants were asked to report if they experienced fatigue or soreness at anytime during the tests.

The ICC estimates for the TtB ml ranged from 0.85-0.94 and for the TtB ap it was 0.85. According to Fleiss index (1986), these ICC estimates are classified as excellent. The ICC estimates reported in this thesis are higher than the findings of Hertel *et al.* (2006), as their ICC estimates ranged from 0.34-0.81 for the TtB ml and from 0.5-0.87 for the TtB ap. However, their study's aim was to evaluate the intrasession reliability not test retest reliability. Their sample was larger (24 participants), younger (20.8 ± 2.4 years), all participants were females and were only tested while their eyes were opened. They also used ICC (2,1) to calculate the reliability estimate while ICC (3,k) was used in this study. Different ICC equations are expected to yield different ICCs (Weir 2005; Shrout and Fleiss 1979). Another difference between

the design of this study and the one by Hertel *et al.* (2006) is that they reported separate reliability estimates for the right and left foot while the reliability estimates in this study were calculated after pooling the data from both feet together.

The ICC estimates for the 1-choice RT ranged from 0.53-0.92, for the 2-choice RT ranged from 0.60 -0.80, for the 1-choice SM ranged from 0.94-0.95 and for the 2-choice SM ranged from 0.70-0.89. These ICCs are either excellent (ICC > 0.75) or fair to good (ICC 0.40-0.75). Three variables had considerably lower ICCs than the others (1-choice RT up, 2-choice RT up and 2-choice SM L). However, the ICC should always be interpreted in the context of the tested population and in combination with other estimates of reliability. The sample were six participants who were homogenous in their characteristics, this might have caused this result. The standard error of measurement for these variables in line with the estimates of the other measures (table 3). Therefore, considering the small size, characteristics of the sample and given that there will be no attempt at generalising these reliability estimates beyond this thesis, all the variables will be used in this research.

The test retest reliability of the RT and SM as measured by the Human Performance Measurement/ Basic Elements of performance equipment (BEP-1)[7] was evaluated by Kauranen and Vanharanta (1996). Their ICC for the 2-choice RT ranged from 0.70-0.75 and for the 2-choice SM, ranged from 0.88-0.91. While their standard error of measurements estimates were 0.174 m/s and 0.217m/s for the 2-choice RT and SM respectively. The ICC values reported in this study could not be compared with the ICC values of Kauranen and Vanharanta (1996) because their method of ICC calculation is not known. Bearing in mind that different equations could yield different estimates, such a comparison would be misleading. However, it is important to evaluate the relevance of the reliability estimates reported by Kauranen and Vanharanta (1997) because the three key studies[8] on tennis elbow similar to this PhD research referred only to it as a proof of reliability for the RT and SM measures they have used.

[7] As mentioned earlier in this chapter, the equipment used in this PhD program was designed to be similar to the functions and design of the BEP 1.
[8] Pienimaki *et al.* (1997), Bisset *et al.* (2006) and Bisset *et al.* (2009).

Although Kauranen and Vanharanta used a larger sample size (n=40), there are some issues that need to be addressed in their study. Firstly; all participants were females, this challenges the generalisability of the findings to a male population especially as gender differences in RT and SM were statistically significant according to the same study. Secondly; the method of calculation of the reliability estimates was not mentioned, therefore, the appropriateness of their analysis could not be judged or reproduced which could be misleading and is classified as poor practice in research (Weir 2005; Hopkins 2000). Finally; they have only evaluated the reliability estimates of the 2-choice RT and SM of the right upper and lower limb. This restricts the generalisability of the findings to the other measures of RT and SM. Interestingly, the other studies (see footnote 8) used the same article to justify the reliability of the 1-choice RT and 1-choice SM that were not evaluated for reliability in the first place.

The test and retest sessions in the reliability study for the TtB in this thesis were separated by two weeks and the retest was carried out at the same time of the day as the first test. This would control any physiological variations in performance that might exist due to the circadian rhythm pattern. Other precautions made to limit the differences between the test and retest included asking the participants to make their day routine on the retest day similar to what they did on the first test. Participants were also checked for any acute pathology and if they took any medications that might affect their performance.

3.5.1 Limitations of the reliability studies

The small sample size might be an issue here as n=6 and n=7 in the TtB and RT/SM reliability studies respectively. However, it is important to bear in mind that the participants' variability affects the reliability more than the sample size (Morrow and Jackson 1993). The number of participants needs to be considered though, as population parameters are more likely to be approached by the reliability estimates in larger sample sizes (Morrow and Jackson 1993). Given that the aim of the two reliability studies reported in this thesis, was not to establish reliability of the tested measures for generalisation purposes beyond the confines of this research the reliability estimate results obtained here are acceptable as long as they are interpreted in the context of the

research of this thesis. This notion is supported by Morrow and Jackson (1993) who suggested that reliability estimates obtained from pilot studies need to be viewed as descriptive statistics that do not provide any definitive information.

The debate about small sample size in reliability studies is not in regard to statistical significance. The magnitude of the reliability estimates is the issue of concern here. Small sample sizes usually have a wide range of confidence intervals so larger standard error is expected especially that values of the lower limit of the 0.95 interval might approach zero (Morrow and Jackson 1993).

Another limitation is the equipment used in the balance test as two force platforms were used (Kistler built-in force platform and Kistler portable force platform). The portable force platform was used only once. Typically, a test retest reliability study will involve the use of only one equipment (Hopkins 2000). However, for the purposes of this study this could not be achieved due to laboratory booking practicality and availability of participants. It could be argued that in the context of this thesis, the use of two equipments is rather advantageous here because the main data collection for the balance study requires the use of the two equipments. Furthermore, no literature was found in regard to differences between the two equipments but the expectation of difference in readings is small.

3.5.2 Conclusion

The test retest reliability estimates reported in this thesis revealed that TtB, RT and SM are reliable, rating excellent or fair to good on the Fleiss (1986) index. Therefore, these measures will be used throughout this thesis with confidence.

Chapter 4

Data Analysis and Results

Chapter 4: Data Analysis and Results

4.1 Introduction

The quasi experimental design used in this study was mixed, repeated measures between participants, also known as a split-plot design. The inferential statistical analysis of choice was mixed design ANOVA and the software used for data analysis was SPSS (version 18 IBM, Somers, NY). This study includes two major sets of data; balance data and response time data. Each set of data were analysed separately. Before reporting the results, the chosen statistical tests were justified, assumptions were checked thoroughly and corrections were applied as applicable. Every effort was made to ensure that the analysis was performed correctly in order to yield a reliable interpretation of the data. This introduction includes a brief description of the content of this chapter followed by a simple outline of the analysis tests carried out. However, a detailed and in depth critique of every statistical test is presented later under its corresponding heading.

The first section of this chapter includes the analysis of balance data. The dependent variables for the balance data were TtB ap and TtB ml. For each variable, descriptive statistics were calculated then data were plotted using box plots to identify outliers. When parametric assumptions were checked, the assumption of normality was not satisfied, therefore, data were transformed in order to correct the normality violations. Despite different data transformation some normality violations remained uncorrected. Before proceeding to mixed design ANOVA, the robustness of ANOVA test under violations versus other robust tests was reviewed. Finally the untransformed data of time to boundary were analysed using mixed design ANOVA. The results were interpreted in the light of statistical significance value, the effect size and using interaction graphs.

The second section of this chapter includes the analysis of RT and SM data. The dependent variables were; 1-choice RT/ SM upper limb, 1-choice RT/ SM lower limb, 2-choice RT/ SM upper limb and 2-choice RT/ SM lower limb. For each variable,

descriptive statistics were calculated then data were plotted using box plots to identify outliers. Response time outliers were included in the analysis while speed of movement outliers were treated as missing data. When parametric assumptions were checked, the assumption of normality and homogeneity of variance were not satisfied. Therefore, data were transformed in order to correct these violations. Despite different data transformations, some normality violations remained uncorrected. However, the homogeneity of variance violations in the response time data were corrected using the log transformation and the square root transformation. The former was used in the final analysis given the nature of the original data and the ability to interpret the analysed log transformed data. Along with the violations in homogeneity of variance in the speed of movement data, there have been other issues in the experimental equipment design and the protocol of data collection. Therefore, speed of movement was excluded from the analysis. Before proceeding to mixed design ANOVA, the robustness of the ANOVA test under violations versus other robust tests was reviewed. Finally the log transformed data of response time were analysed using mixed design ANOVA and results were interpreted in the light of statistical significance value, the effect size and using interaction graphs. Flowcharts for the RT, SM and TtB data analysis are presented in Figure 22 and 23. These flow charts demonstrate the decision making process involved in the data analysis of this research.

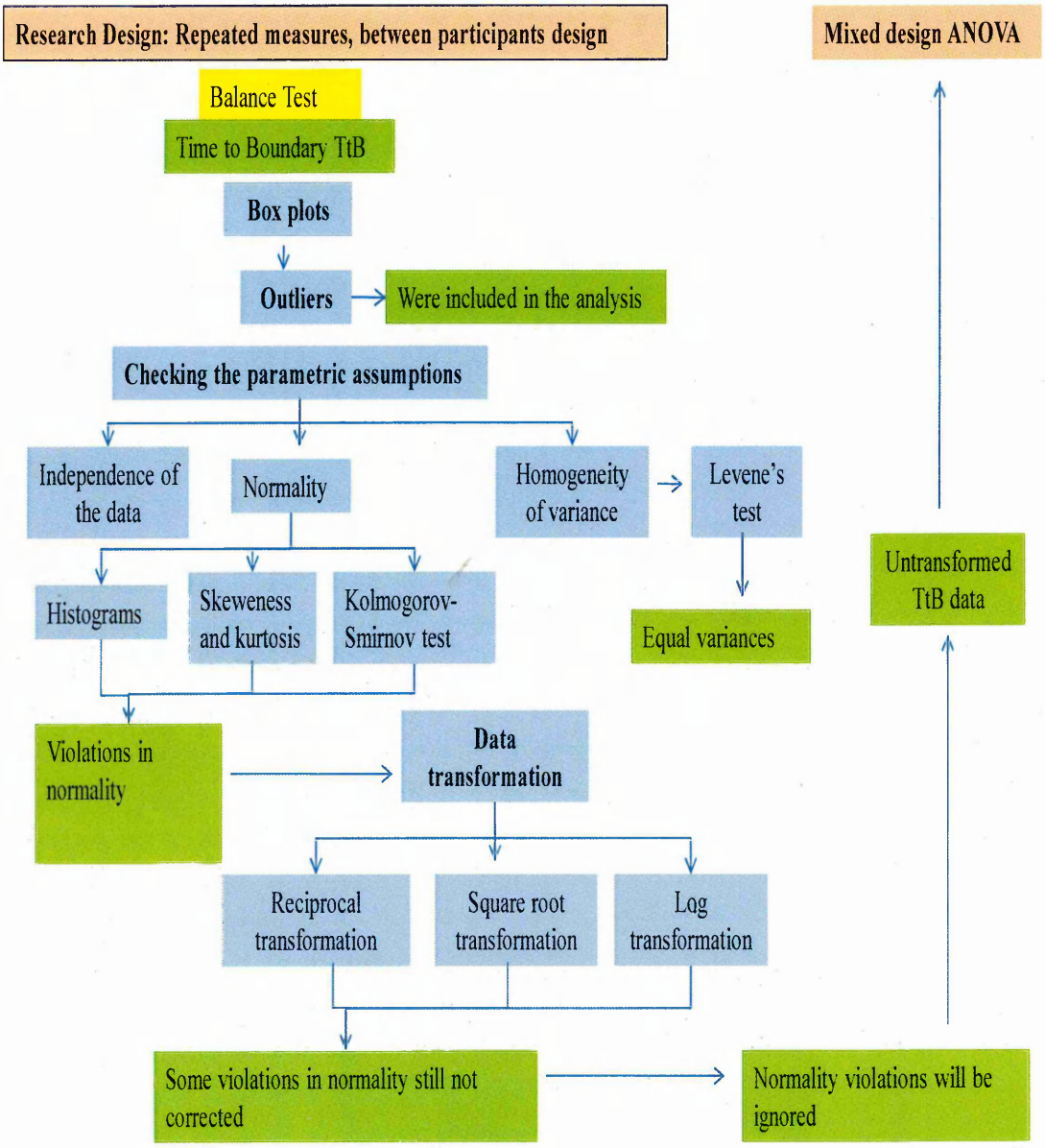

Figure 22: Outline for the Time to boundary data analysis.

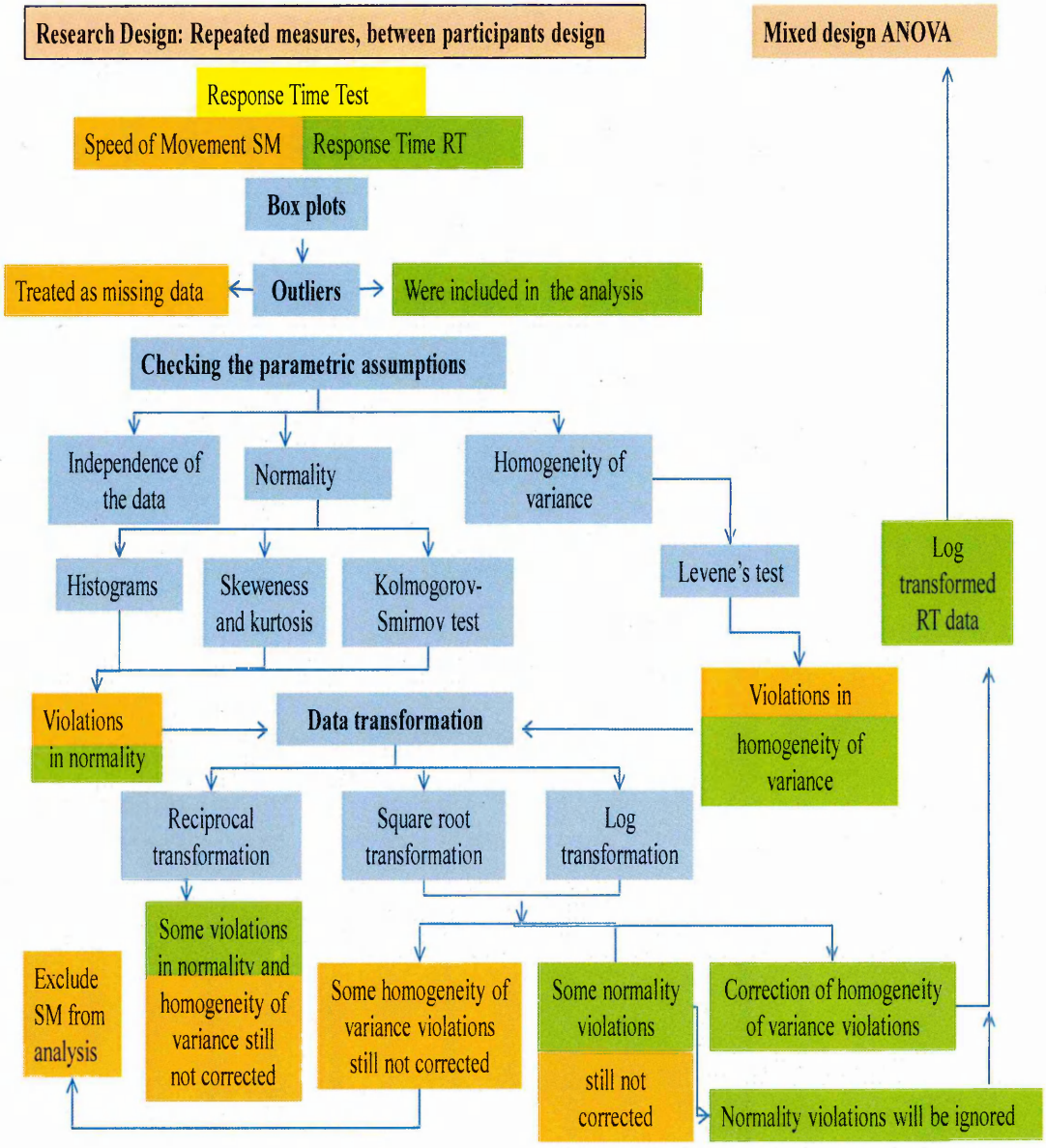

Figure 23: Outline for the response time and speed of movement data analysis.

4.2 Balance Data: Time to Boundary ap and ml

4.2.1 Descriptive statistics

	Descriptive statistics	Healthy participants (n=22)			
		Closed eyes/ Dominant LL	Closed eyes/ Non dominant LL	Opened eyes/ Dominant LL	Opened eyes/ Non dominant LL
TtB ap (sec)	Mean	0.528	0.621	1.818	1.935
	Std. Dev	0.225	0.277	0.640	0.665
TtB ml (sec)	Mean	0.185	0.184	0.513	0.514
	Std. Dev	0.070	0.076	0.191	0.194

Table 10: Descriptive statistics for TtB in healthy participants.

	Descriptive statistics	Patients with tennis elbow (n=11)			
		Closed eyes/ Ipsi-lateral LL	Closed eyes/ Contra-lateral LL	Opened eyes/ Ipsi-lateral LL	Opened eyes/ Contra-lateral LL
TtB ap (sec)	Mean	0.446	0.475	1.433	1.574
	Std. Dev	0.259	0.244	0.580	0.447
TtB ml (sec)	Mean	0.166	0.187	0.432	0.535
	Std. Dev	0.093	0.092	0.118	0.253

Table 11: Descriptive statistics for TtB in patients with tennis elbow.

4.2.2 Statistical analysis

4.2.2.1 Outliers in the time to boundary data

Before performing any statistical analysis, the TtB data were plotted using simple box plots so outliers could be identified. Four outliers were identified in the patients group; three were in the TtB ap-Opened eyes/Contra-lateral lower limb and one in the TtB ml-Opened eyes/Contra-lateral lower limb (Appendix 2/ section 1.2), outliers are marked as an asterisk. By definition an outlier is a score that is markedly distant from the other scores and it might bias the mean of the data. However, there are a number of solutions that might minimise the impact of outliers; one way is to remove the score, in other words delete the data of that particular participant or treat it as missing. However, this would not be appropriate because these extreme scores came from patients who represent the population of interest (patients with chronic tennis elbow). Possible reasons for their extreme readings will be discussed later but for the time being excluding the data of these participants will bias the findings obtained from

this group. Other ways of dealing with outliers include transforming data which will be reviewed in detail later on in this chapter.

4.2.2.2 Checking the assumptions

Before doing parametric tests it is important to check the following assumptions: normal distribution of the data, homogeneity of variance and independence of the data. It is important to check that these core assumptions are met, otherwise the inferential statistical analysis would not function as it intended and the interpretation of findings could be misleading as a result of type I error[9] (Lix *et al.* 1996; Keselman *et al.* 1998).

The TtB data satisfies the assumption of independence by default. Therefore, two assumptions need to be checked, normality and homogeneity of variance. Normality was checked using histograms, Q-Q plots, skewness and kurtosis scores and Kolmogorov-Smirnov (K-S) test. Levene's test was used to test homogeneity of variance. The TtB data was homogenous but were non-normally distributed in four variables out of the sixteen. See Appendix 2/ section 1.3 for a detailed assumptions check.

4.2.2.3 Transforming data

In order to correct the non-normally distributed data, the entire TtB data were transformed using three different transformations; log transformation, square root and reciprocal transformation. These transformations were chosen because they can correct positive skew (Field 2009). The transformed TtB data were then plotted using histograms and K-S test was conducted to check if the transformed data significantly differs from a normal distribution. However, even after the various transformations, some of the TtB data distributions remained non-normal. Refer to Appendix 2/ section 1.3 for a detailed assumptions check.

4.2.2.4 Mixed ANOVA vs. robust tests

To sum up, the TtB data satisfied two of the assumptions because it was independent and homogeneous. However the assumption of normality was violated in four out of the sixteen variables. Data were transformed in order to correct the non-

[9] Type I error occurs when the null hypothesis is rejected when it is true and should have been accepted, which means there is a genuine effect when actually there is not (Field 2009).

normality but that was not successful. Non-parametric tests which are assumption free are not applicable in this case because there is no equivalent non-parametric test for mixed ANOVA (Field 2009).

One solution is to use robust tests to carry out the analysis as they are effective in dealing with non-normality problem (Wilcox 2005). A robust test is one that can be used when there is a violation in the assumption and still produces an accurate statistical model (Field 2009). There were two options for robust tests; either to use the bootstrapping function on SPSS or run the R program with SPSS plugins, the former is easier while the latter is rather technical. However, due to limited resources, the robust test was not used in the analysis of this data.

Mixed factorial ANOVA could also be run under the normality violation. There is a debate in the literature whether the ANOVA test is robust or not, although some claim that ANOVA can be used under broken violations; some evidence suggest that ANOVA is sensitive to the assumptions violations. Running ANOVA might have the risk of type I error and affecting the statistical power, therefore, alternative robust tests are recommended to guarantee that interpretation of the findings is valid and accurate (Lix *et al.* 1996, Keselman *et al.* 1998). However, those who support the use of ANOVA under violations are not solely concerned if the assumptions are met or not, rather they are concerned whether the severity of these violations is enough to undertake different analytical approach (Lix *et al.* 1996). In the light of no existing valid test to quantify the severity of the violations, the decision to use ANOVA or not should be made by the researcher on the ground of deep understanding of the nature of the data and the context of the research (Lix *et al.* 1996).

For the purposes of this study and taking into account the available resources, mixed ANOVA was used to analyse the TtB data for the following reasons: firstly; for the TtB data only 4 variables out of the total 16 were non-normally distributed and given that the same participants did all the variables we opted to ignore the violations in normality. Secondly, violation of normality is less serious violation compared to independence of data and homogeneity of variance as ANOVA is simply not robust to violation in homogeneity if the groups are not equal and type I error is largely inflated when the data is not independent (Field 2009). Nevertheless, it is noteworthy while

interpreting the findings of the non normal data to keep in mind that when the group sizes are not equal the skewness in data might affect the accuracy of F while its power could also be affected by the nonnormality.

4.2.2.5 Interpreting the findings of mixed ANOVA

The interpretation of the findings was based on the significance p value along with the effect size r and interaction graphs. The rationale behind interpreting these three elements is introduced next, and then the results of mixed ANOVA are presented.

4.2.2.5.1 *p* value and effect size

The null hypothesis testing with its significance p value are the dominating factors of the decisions made in health and biomechanics quantitative research. Researchers trust that their scientific rigour is established when relying on the objective threshold of the p value. However, previous authors have suggested that depending on the p value alone could be misleading. Therefore, the use of the p value is recommended to be supported by other statistical measures like the effect size (Field 2009; Levine and Hullett 2002; Mullineaux *et al.* 2001).

Effect size is an objective descriptive statistic measure that provides a quantification of the magnitude of the effect (Field 2009, Mullineaux *et al.* 2001). Effect size helps in understanding the usefulness and the importance of the significant values; therefore it supports an informed decision about the acceptance or rejection of the null hypothesis. As a result type I and type II error could be avoided (Mullineaux *et al.* 2001). There are different ways to calculate the effect size; this depends on the design of the research and the statistical test used for analysis. For mixed design ANOVA, eta squared could be calculated but it is biased as it overestimates the effect (Levine and Hullett 2002). SPSS produces partial eta squared, however, this was not used in this study because it is less conservative than eta squared and its values are not additive as they may sum up greater than 1 which makes it difficult to interpret (Levine and Hullett 2002). It is preferable to use omega squared instead but it is rather complicated to calculate in mixed ANOVA and can only be used in equal number groups; therefore the following formula recommended by Field (2009) was used to calculate Pearson's correlation coefficient r:

$$r = \sqrt{\frac{F(1,df_R)}{F(1,df_R)+ df_R}}$$ [10] **(Equation 4.1)**

Pearson's correlation coefficient r lies between 0 and 1; the latter represents a perfect effect while the former represents no effect. Table 9 includes some suggestions made by Cohen (1992) that are commonly used as a guide to quantify small, medium and large effects.

r	Index
.10	Small effect
.30	Medium effect
.50	Large effect

Table 12: *r* index by Cohen 1992.

4.2.2.5.1 Interaction graphs

These graphs show the interaction between independent variables which is helpful in interpreting the data because significance values only tell us if there is a difference but they do not provide details about the direction or the nature of that difference. Independent variables are plotted as lines, where parallel lines indicate no difference while intersecting lines indicate a strong interaction between these variables. All the interaction graphs presented in this chapter were produced in Excel 2007.

4.2.2.6 Mixed Design ANOVA/ TtB ap

There was a substantial main significant effect of the eyes $F(1,31) = 177.720$, $p < 0.05$, $r = 0.92$, which means that TtB ap was significantly different between the eyes closed and eyes opened conditions. There was also a significant main effect of the dominance/ laterality of the lower limb $F(1,31) = 4.641$, $p < 0.05$, $r = 0.36$. This indicates that TtB ap was significantly different when participants were standing on their dominant lower limb as compared to their non dominant one or when patients with tennis elbow were standing on their ipsi-lateral lower limb as compared to their contra-lateral one. None of the interactions were significant and all have small effect size. There was no significant effect of tennis elbow $F(1,31) = 3.192$, but it approaches significance at $p = 0.084$ and it has a medium effect size, $r = 0.31$. This indicates that

[10] (Field 2009, p:532)

time to boundary in the anterioposterior direction for healthy participants and patients with tennis elbow were in general the same. (See Appendix 2/ section 1.5 for the SPSS output of mixed design ANOVA). Table 10 is a summary of the effect sizes and significance values for all the independent variables.

Variable	Effect size		Significance (p)
Tennis elbow	0.31	Medium effect	Non significant
Eyes	0.92	Large effect	$p<0.001$
Eyes x Tennis elbow	0.26	Small effect	Non significant
Dominance/Laterality	0.36	Medium effect	$p<0.05$
Dominance /Laterality x Tennis elbow	0.04	Negligible effect	Non significant
Eyes x Dominance /Laterality	0.15	Small effect	Non significant
Eyes x Dominance /Laterality x Tennis elbow	0.1	Small effect	Non significant

Table 13: Effect size and p values for the variables of TtB ap.

Next the interaction effects were plotted using interaction graphs, these graphs are discussed in the light of significance values and effect size. The levels of the independent variables are shown in Table 11.

Independent variables	Levels	
Between participants independent variable	Healthy participants group	
	Patients with tennis elbow group	
Within participants independent variables	Eyes (2 levels)	Eyes closed
		Eyes opened
	Dominance/ Laterality (2 levels)	Dominant lower limb in healthy or Ipsi-lateral lower limb in patients
		Non dominant lower limb in healthy or Contra-lateral lower limb in patients

Table 14: Levels of independent variables for the balance data (TtB ap and ml).

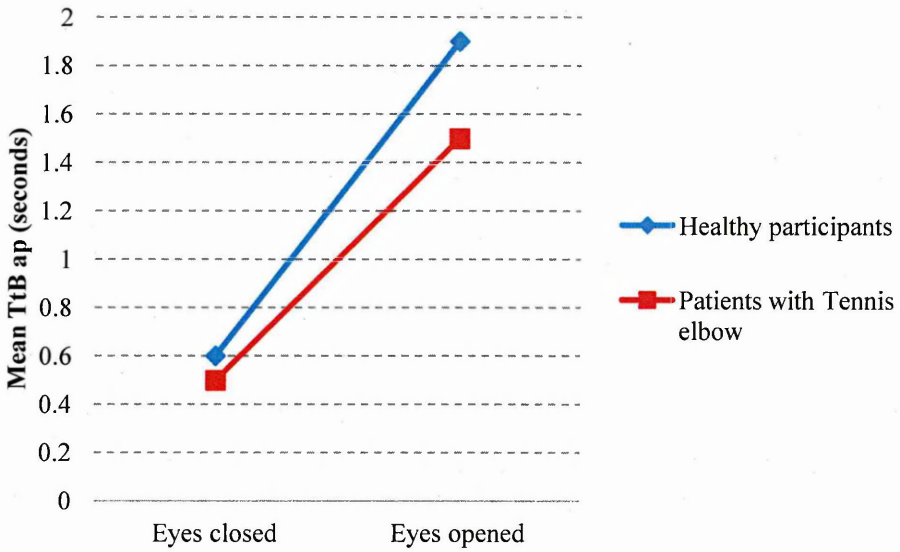

Figure 24: Interaction graph for Eyes x Tennis elbow in TtBap.

The aim of the interaction illustrated in Figure 24 is to investigate if the difference between healthy participants and patients with tennis elbow is the same for the eyes closed and eyes opened condition. This interaction was not significant, $F(1,31) = 2.165$, $p = 0.151$, but it had a small effect size, $r = 0.26$. The interaction shows that TtBap was much shorter in the eyes closed condition than the eyes opened condition for both groups. However, patients with tennis elbow had shorter TtBap in the eyes closed and eyes opened conditions. This suggests that in general they were more susceptible to falling than the healthy participants.

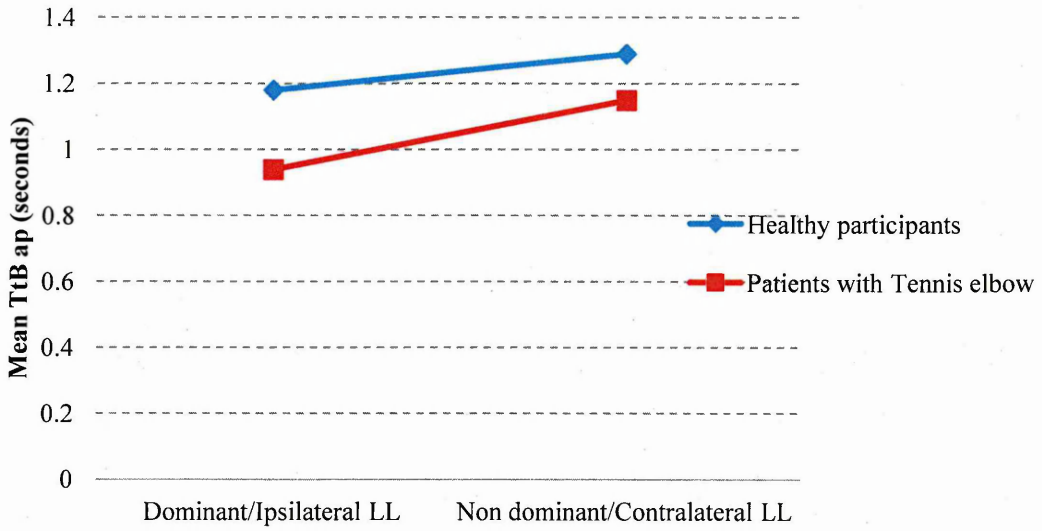

Figure 25: Interaction graph for Dominance/Laterality x Tennis elbow in TtBap.

The aim of the interaction illustrated in Figure 25 is to investigate if the difference between healthy participants and patients with tennis elbow is the same for dominant/ ipsi-lateral lower limb and non dominant/ contra-lateral lower limb. This interaction was not significant $F(1,31) = 0.056$, $p = 0.815$, and also had a negligible effect size, $r = 0.04$. Actually the lines are fairly parallel indicating that the healthy participants had shorter TtBap when they were standing on their dominant lower limb, and the same is true for patients with tennis elbow, they had shorter TtBap when they were standing on their ipsi-lateral lower limb.

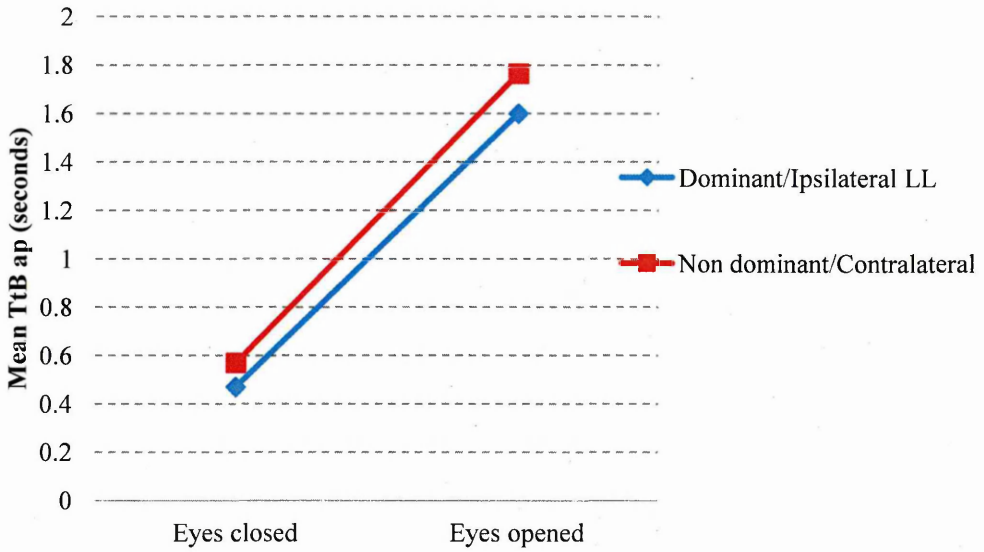

Figure 26: Interaction graph for Eyes x Dominance/Laterality in TtBap.

The aim of the interaction illustrated in Figure 26 is to investigate if the difference between dominant/ipsi-lateral lower limb and non dominant/contra-lateral lower limb is the same for the eyes closed and eyes opened condition. This interaction was not significant $F(1.31) = 0.747$, $p = 0.394$, with small effect size, $r = 0.15$. The TtBap was shorter in the eyes closed condition for both the dominant/ipsi-lateral and non dominant/contra-lateral lower limb.

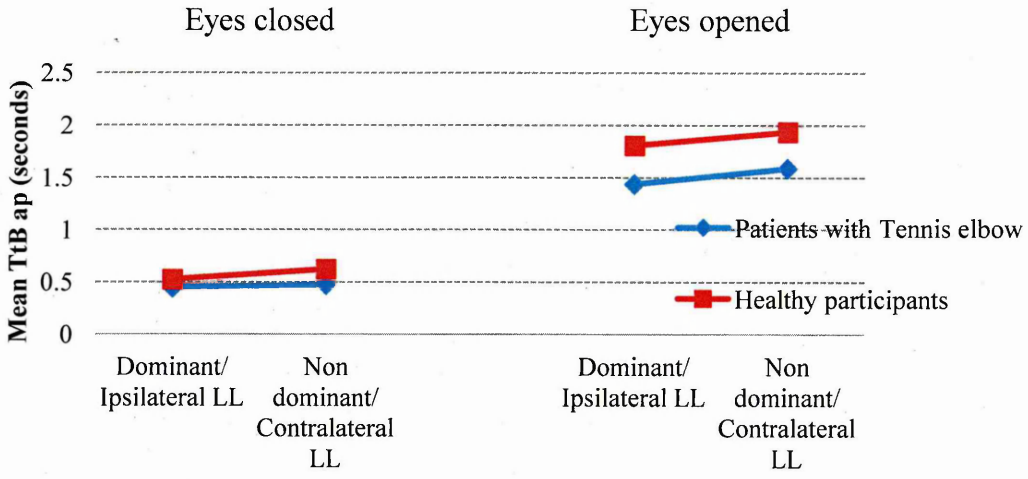

Figure 27: Interaction graph for Dominance x Tennis elbow x Eyes in TtBap.

The aim of the three way interaction illustrated in Figure 27 is to investigate the difference between healthy participants and patients with tennis elbow for the dominant/ipsi-lateral and non dominant/contra-lateral lower limb for the eyes closed versus eyes opened condition. This interaction was not significant $F(1.31) = 0.303$, $p = 0.586$, and had a small effect size, $r = 0.1$. In the eyes closed condition, TtBap was shorter when patients and healthy participants were standing on their ipsi-lateral/ dominant lower limb, however, the decrease in the TtBap was greater for healthy participants as the red line connecting the squares is steeper. For the eyes opened condition, the lines are fairly parallel, indicating that both the healthy participants and patients with tennis elbow had shorter TtBap when they were standing on their dominant/ipsi-lateral lower limb respectively.

4.2.2.7 Mixed Design ANOVA/ TtB ml

There was main significant effect of the eyes $F(1, 31) = 140.264$, $r = 0.9$, indicating that TtB ml was significantly different between eyes opened and eyes closed conditions. Although the Dominance/ Laterality variable was not significant $F(1,31) = 3.275$, $r = 0.31$, its p value approaches significance at 0.08 and it also has medium effect size. This means that there was a noticeable difference in the TtB ml between the dominant/non dominant foot and ipsi-lateral/contra-lateral foot. None of the interactions were significant, it is noteworthy to mention that the interaction between foot and tennis elbow approaches significance at $F(1,31) = 3.267$, $p = 0.08$ and it has a medium size effect $r = 0.31$. There was no significant effect of tennis elbow $F(1,31) < 1$, $r = 0.003$. This indicates that time to boundary in the mediolateral direction from healthy participants and patients with tennis elbow were in general the same. (See Appendix 2/ section 1.4 for the SPSS output of mixed design ANOVA). Table 12 is a summary of the effect sizes and significance values for all the independent variables.

Variable	**Effect size**		**Significance (p)**
Tennis elbow	0.08	Negligible effect	Non significant
Eyes	0.9	Large effect	$p<0.0001$
Eyes x Tennis elbow	0.07	Negligible effect	Non significant
Dominance/Laterality	0.31	Medium effect	Non significant
Dominance/ Laterality x Tennis elbow	0.31	Medium effect	Non significant
Eyes x Dominance/ Laterality	0.23	Small effect	Non significant
Eyes x Dominance/ Laterality x Tennis elbow	0.22	Small effect	Non significant

Table 15: Effect sizes and p values for the variables of TtB ml.

Next the interaction effects are plotted using interaction graphs, these graphs are discussed in the light of significance values and effect size.

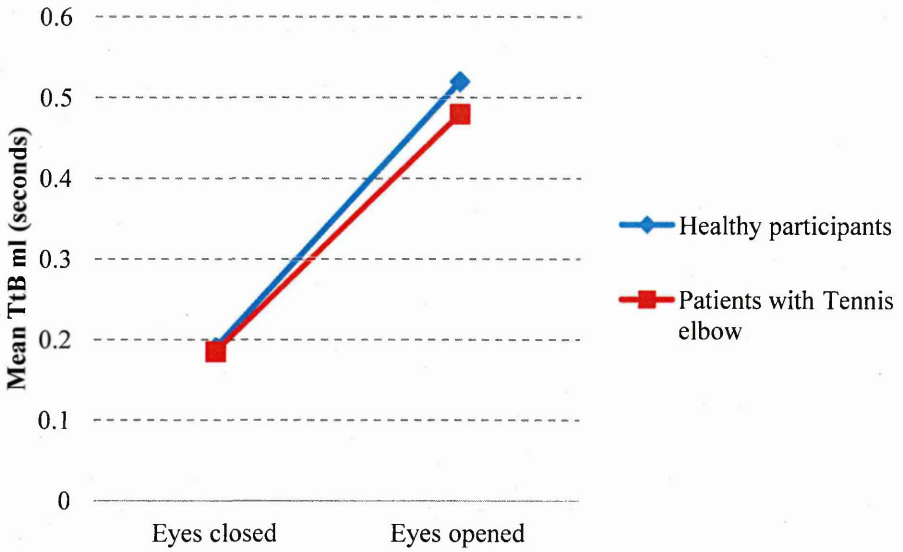

Figure 28: Interaction graph for Eyes x Tennis elbow in TtBml.

The aim of the interaction illustrated in Figure 28 is to investigate if the difference between healthy participants and patients with tennis elbow is the same for the eyes closed and eyes opened condition. This interaction was not significant, $F(1,31) = 0.173$, $p = 0.680$, and less than small effect size. The interaction shows that TtBap was much shorter in the eyes closed condition than the eyes opened condition for both groups. If compared to the interaction graph in Figure 24, the difference between TtBml in eyes closed and eyes opened is less than the difference of TtBap in both visual conditions which suggests that both groups displayed more stability in the ml direction while they were more susceptible to falling in the ap direction.

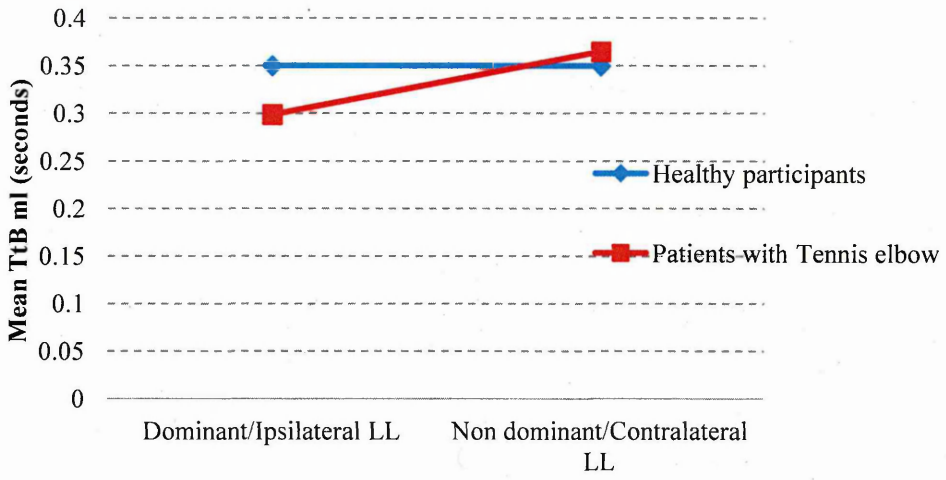

Figure 29: Interaction graph for Dominance/ Laterality x Tennis elbow in TtBml

The aim of the interaction illustrated in Figure 29 is to investigate if the difference between healthy participants and patients with tennis elbow is the same for dominant/ ipsi-lateral lower limb and non dominant/ contra-lateral lower limb. Although this interaction was not significant $F(1,31) = 3.267$, *ns,* it approaches significance at $p = 0.08$ and it has a medium effect size at $r = 0.31$, which is also reflected in the different pattern of results of patients with tennis elbow and healthy participants (intersecting lines). Healthy participants had the same TtBml whether they were standing on their dominant or non dominant lower limb. On the other hand, patients with tennis elbow had shorter TtBml when they were standing on their ipsi-lateral.

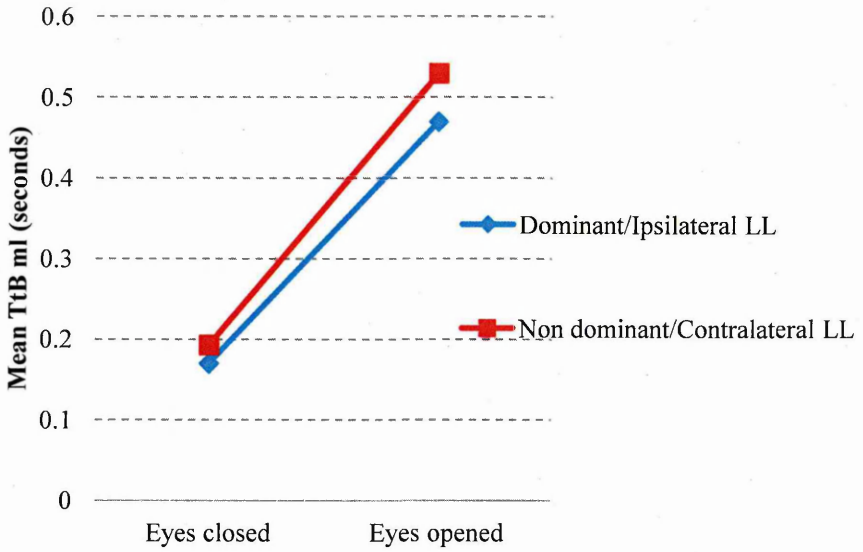

Figure 30: Interaction graph for Eyes x Dominance/ Laterality in TtBml.

The aim of the interaction illustrated in Figure 30 is to investigate if the difference between dominant/ipsi-lateral lower limb and non dominant/contra-lateral lower limb is the same for the eyes closed and eyes opened condition. This interaction was not significant $F(1.31) = 1.752$, $p = 0.195$, and had a small effect size. Both lower limbs had similar TtBml in both visual conditions.

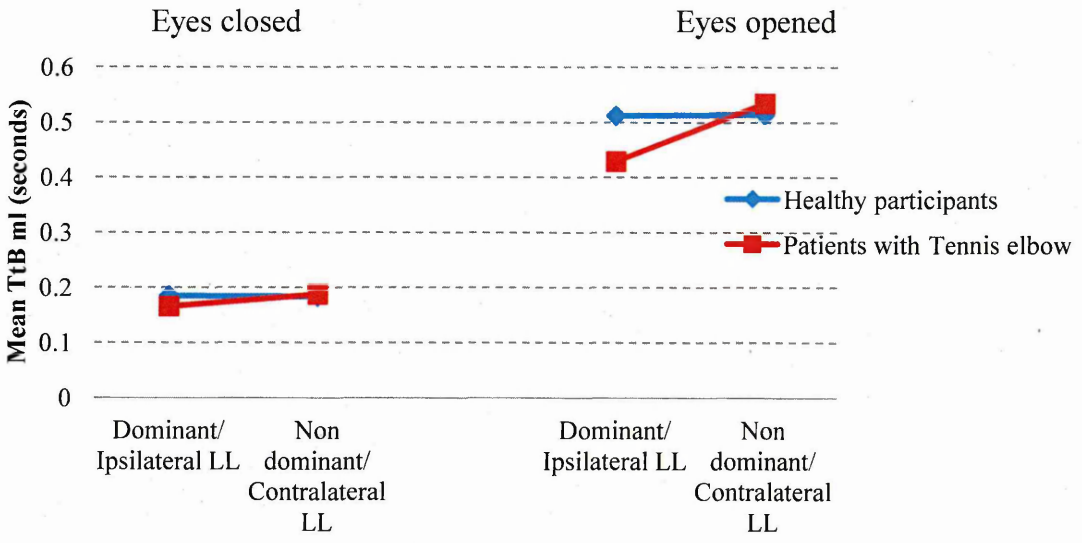

Figure 31: Interaction graph for Dominance/ Laterality x Tennis elbow x Eyes in TtBml.

The aim of the three-way interaction illustrated in Figure 31 is to investigate the difference between healthy participants and patients with tennis elbow for the dominant/ipsi-lateral and non dominant/contra-lateral lower limb in the eyes closed as compared to the eyes opened condition. This interaction was not significant $F(1.31) = 1.619$, $p = .213$, and had small effect size. The intersecting lines show the different pattern of results of healthy participants and patients with tennis elbow when standing on their dominant/ipsi-lateral lower limb as compared to standing on their non dominant/contra-lateral lower limb. Healthy participants had a slight decrease in their TtBml when they were standing on their non dominant lower limb, while patients with tennis elbow had an extreme drop of their TtBml when they were standing on their ipsi-lateral lower limb.

Different pattern of results could be also identified in healthy participants and patients with tennis elbow when standing on their dominant/ipsi-lateral lower limb as compared to standing on their non dominant/contra-lateral lower limb during the eyes opened condition. Healthy participants had almost the same TtBml for their dominant and non dominant lower limb, while patients with tennis elbow had a noticeable decrease of their TtBml when they were standing on their ipsi-lateral lower limb. When compared to the interaction graph in Figure 25, it is obviously seen that for both visual

conditions there is a different pattern of TtB results in the ap and ml direction in both groups.

4.2.3 Descriptive analysis of the length of the balance test

The results of a mixed ANOVA showed that TtB in the ap direction was not significantly different between healthy participants and patients with tennis elbow, however, the p value approached significance at $p = 0.08$ and it also had a medium effect size. In line with the previous discussion around statistical and clinical significance, this finding will not be discarded and its clinical relevance will be discussed. Nevertheless, it is important to understand this finding in context; therefore, some issues around the data collection will be highlighted as these could have influenced the findings. One issue to consider is the duration of the balance data analysed, which was for the first ten seconds of single leg standing. However, the Bioware software was set to collect data for up to one minute; participants were instructed to stand on one leg at least for ten seconds but they should stand longer if they can. It was noticeable that healthy participants were able to stand balanced for longer period of times when compared to patients with tennis elbow. This is demonstrated in table 16 and 17.

Descriptive statistics	Healthy participants (n=22)			
	Closed eyes/ Dominant LL	Closed eyes/ Non dominant LL	Opened eyes/ Dominant LL	Opened eyes/ Non dominant LL
Mean	23.26	22.45	60.00	59.72
Std. Dev	12.32	10.11	0.02	1.28
1 minute[12]	2	0	21	21

Table 16: Descriptive statistics of the length of the balance test in healthy participants.

Descriptive statistics	Patients with tennis elbow (n=11)			
	Closed eyes/ Ipsi-lateral LL	Closed eyes/ Contra-lateral LL	Opened eyes/ Ipsi-lateral LL	Opened eyes/ Contra-lateral LL
Mean	14.28	13.36	19.09	20.07
Std. Dev	3.35	3.21	7.17	7.86
1 minute	0	0	2	3

Table 17: Descriptive statistics of the length of the balance test in patients with tennis elbow.

[12] This represents the number of participants who managed to stand on one leg for one minute.

Healthy participants stood for longer in all the conditions when compared to the patients group. Also, almost all the healthy participants managed to stand on one leg for one minute in the eyes opened condition while few patients managed to do that. It seems that the duration of ten seconds single leg standing was not enough to reveal significant differences between the two groups.

Although the results shown in Table 16-17 are only descriptive, they are of paramount importance to the original hypothesis of this work as they clearly show a noticeable difference in balance between healthy participants and patients with chronic tennis elbow. Future research should take the length of the balance test into consideration as timing the balance test is one of the most common methods used by physiotherapists to assess balance in a clinical setting.

4.3 Response time data

There are four sets of data; 1-choice RT and SM variables of the upper limb, 1-choice RT and SM variables of the lower limb, 2-choice response RT and SM variables of the upper limb and 2-choice RT and SM variables of the lower limb (See Table 13 and 14). Analysis will be carried out on each set of data separately.

	Response time and speed of movement variables of the upper limb
1	1-choice response time dominant/ affected upper limb
2	1-choice speed of movement dominant/ affected upper limb
3	1-choice response time non dominant/ non-affected upper limb
4	1-choice speed of movement non dominant/ non-affected upper limb
5	2-choice response time dominant/ affected upper limb same side target
6	2-choice response time dominant/ affected upper limb other side target
7	2-choice speed of movement dominant/ affected upper limb same side target
8	2-choice speed of movement dominant/ affected upper limb other side target
9	2-choice response time non dominant/ non-affected upper limb same side target
10	2-choice response time non dominant/ non-affected upper limb other side target
11	2-choice speed of movement non dominant/ non-affected upper limb same side target
12	2-choice speed of movement non dominant/ non-affected upper limb other side target

Table 18: Response time and speed of movement variables of the upper limb.

	Response time and speed of movement variables of the lower limb
1	1-choice response time dominant/ ipsi-lateral lower limb
2	1-choice speed of movement dominant/ ipsi-lateral lower limb
3	1-choice response time non dominant/ contra-lateral lower limb
4	1-choice speed of movement non dominant/ contra-lateral lower limb
5	2-choice response time dominant/ ipsi-lateral lower limb same side target
6	2-choice response time dominant/ ipsi-lateral lower limb other side target
7	2-choice speed of movement dominant/ ipsi-lateral lower limb same side target
8	2-choice speed of movement dominant/ ipsi-lateral lower limb other side target
9	2-choice response time non dominant/ contra-lateral lower limb same side target
10	2-choice response time non dominant/ contra-lateral lower limb other side target
11	2-choice speed of movement non dominant/ contra-lateral lower limb same side target
12	2-choice speed of movement non dominant/ contra-lateral lower limb other side target

Table 19: Response time and speed of movement variables of the lower limb.

4.3.1 Descriptive statistics

4.3.1.1 One-choice response time and speed of movement in the upper limb

Group	Descriptive statistics	1-choiceRT Dominant/ Affected upper limb	1-choiceSM Dominant/ Affected upper limb	1-choiceRT Non dominant/ Non Affected upper limb	1-choiceSM Non dominant/ Non Affected upper limb
Healthy participants	Mean	0.275	0.848	0.270	0.754
	Std. Deviation	0.031	0.301	0.031	0.158
Patients with Tennis elbow	Mean	0.285	1.169	0.270	1.005
	Std. Deviation	0.036	0.833	0.044	0.513

Table 20: Descriptive statistics for 1-choice response time and speed of movement in the upper limb (units are in seconds).

4.3.1.2 One-choice response time and speed of movement in the lower limb

Group	Descriptive statistics	1-choiceRT Dominant lower limb	1-choiceSM Dominant lower limb	1-choiceRT Non dominant lower limb	1-choiceSM Non dominant lower limb
Healthy participants	Mean	0.275	0.928	0.274	0.894
	Std. Deviation	0.041	0.227	0.028	0.182
Patients with Tennis elbow	Mean	0.268	0.865	0.284	0.905
	Std. Deviation	0.045	0.296	0.059	0.409

Table 21: Descriptive statistics for 1-choice response time and speed of movement in the lower limb (units are in seconds).

4.3.1.3 Two-choice response time and speed of movement in the upper limb

Group	Descriptive statistics	2-choiceRT Dominant/ Affected upper limb/ same side	2-choiceSM Dominant/ Affected upper limb/ same side	2-choiceRT Non dominant/ Non Affected upper limb/ same side	2-choiceSM Non dominant/ Non Affected upper limb/ same side
Healthy participants	Mean	0.325	0.887	0.309	0.806
	Std. Deviation	0.039	0.247	0.048	0.189
Patients with Tennis elbow	Mean	0.302	1.129	0.301	1.025
	Std. Deviation	0.051	0.478	0.048	0.487

Table 22: Descriptive statistics for 2-choice response time and speed of movement in the upper limb same side target (units are in seconds).

Group	Descriptive statistics	2-choiceRT Dominant/ Affected upper limb/ other side	2-choiceSM Dominant/ Affected upper limb/ other side	2-choiceRT Non dominant/ Non Affected upper limb/ other side	2-choiceSM Non dominant/ Non Affected upper limb/ other side
Healthy participants	Mean	0.334	0.744	0.336	0.701
	Std. Deviation	0.062	0.220	0.053	0.204
Patients with Tennis elbow	Mean	0.310	1.069	0.304	0.940
	Std. Deviation	0.041	0.593	0.064	0.420

Table 23: Descriptive statistics for 2-choice response time and speed of movement in the upper limb other side target (units are in seconds).

4.3.1.4 Two-choice response time and speed of movement in the lower limb

Group	Descriptive statistics	2-choiceRT Dominant/ Ipsilateral lower limb/ same side	2-choiceSM Dominant/ Ipsilateral lower limb/ same side	2-choiceRT Non dominant/ Contralateral lower limb/ same side	2-choiceSM Non dominant/ Contralateral lower limb/ same side
Healthy participants	Mean	0.306	0.838	0.328	0.820
	Std. Deviation	0.047	0.219	0.055	0.187
Patients with Tennis elbow	Mean	0.297	0.894	0.322	1.004
	Std. Deviation	0.051	0.293	0.069	0.563

Table 24: Descriptive statistics for 2-choice response time and speed of movement in the lower limb same side target (units are in seconds).

Group	Descriptive statistics	2-choiceRT Dominant/ Ipsilateral lower limb/ other side	2-choiceSM Dominant/ Ipsilateral lower limb/ other side	2-choiceRT Non dominant/ Contralateral lower limb/ other side	2-choiceSM Non dominant/ Contralateral lower limb/ other side
Healthy participants	Mean	0.316	0.743	0.321	0.765
	Std. Deviation	0.044	0.187	0.050	0.153
Patients with Tennis elbow	Mean	0.325	0.856	0.327	0.692
	Std. Deviation	0.061	0.390	0.093	0.173

Table 25: Descriptive statistics for 2-choice response time and speed of movement in the lower limb other side target (units are in seconds).

4.3.2 Statistical analysis

4.3.2.1 Outliers in the response time and speed of movement data

When the RT and SM data were plotted using box plots, seven outliers were identified, five of them were in the SM. The two outliers in RT belonged to one patient who had bilateral tennis elbow and was the oldest in the group (63 years). Therefore,

outliers in RT were not removed because longer RT might reflect the chronicity of the condition and they are representative of the population of interest, patients with chronic tennis elbow.

On the other hand, the SM outliers were extremely fast scores, a detailed explanation for these scores is provided later under section 4.3.2.3. The normality and homogeneity of variance were checked after removing these outliers. Outliers in SM were treated as missing data and when running the analysis the option of "exclude cases pairwise" was selected which means that for those particular participants that had missing data, only the scores that were missing were excluded from the analysis but their other data points were included in the analysis. Given that the participants who had the outliers had no problem with the other data points, the "pairwise" analysis is more reasonable as the "litwise" analysis excludes the cases with missing variables from the whole analysis. Finally the data with the outliers excluded was transformed using log transformation, square root and reciprocal transformation then checked for normality and homogeneity of variance. (See Appendix 2: section 2.1, 2.3, 2.5 and 2.7 for box plots).

4.3.2.2 Checking the assumptions

Before running mixed design ANOVA, parametric assumptions were checked, the reason for that was discussed before in section 4.2.2.2. The response time data satisfies the assumption of independence by default. Therefore, two assumptions need to be checked, normality and homogeneity of variance.

Next, the results of the normality and homogeneity of variance tests are presented in Table 21 for the RT and SM before and after transformation. The 1-choice RT and SM had no outliers so they were not included next; however data were transformed before the mixed ANOVA analysis.

	1-choice RT-SM UP.L		1-choice RT-SM L.L		
	Normality	**Homogeneity of variance**	**Normality**	**Homogeneity of variance**	**Normality**
All data including outliers	1-choiceSM Dominant/Affected upper limb/Patients $p = 0.015$ 1-choiceRT Non dominant/Non affected upper limb/Healthy. $p = 0.030$ 1-choiceSM Non dominant/Non affected upper limb/ Healthy $p = 0.006$	1-choiceSM Dominant/Affected upper limb $p = 0.010$ 1-choiceRT Non dominant/ Non affected upper limb $p = 0.050$ 1-choiceSM Non dominant/ Non affected upper limb $p = 0.003$	1-choiceRT Non dominant/ Contra-lateral lower limb $p = 0.001$	1-choiceSM Non dominant/ Contra-lateral lower limb $p = 0.015$	2-choiceRT Dominant/ A same side/ Healthy $p = 0.022$ 2-choiceSM Dominant/ A limb/ same side/ Healthy $p = 0.035$ 2-choiceRT Dominant/ A other side/ Healthy $p = 0.001$ 2-choiceSM Dominant/ A limb/ other side/ Patients $p = 0.047$
Data excluding outliers	1-choiceSM Non dominant/Non affected upper limb / Healthy $p = 0.030$ 1-choiceRT Non dominant/Non affected upper limb/ Healthy $p = 0.006$	1-choiceSM Non dominant/ Non affected upper limb. $p = 0.050$ 1-choiceRT Non dominant/ Non affected upper limb. $p = 0.003$			2-choiceSM Dominant/ A limb/ same side/ Healthy $p = 0.022$ 2-choiceRT Dominant/ A other side /Healthy $p = 0.035$ 2-choiceSM Dominant/ A limb/ other side /Healthy $p = 0.001$ 2-choiceRT Dominant/ A same side /Patients $p = 0.047$
Data after log transformatio	log1choiceSM Non dominant/Non affected upper limb/ Healthy $p = 0.023$ log1choiceRT Non dominant/Non affected upper limb/ Healthy $p = 0.015$	log1-choiceSM Non dominant/Non affected upper limb $p = 0.016$		log1choiceSM Non dominant Contra-lateral lower limb $p = 0.010$	log2-choiceRT Dominar limb/ other side/ Patients $p = 0.002$
Data after square root	sqrt1-choiceSM Non dominant/Non affected upper limb / Healthy.016 sqrt1-choiceRT Non dominant/Non affected upper limb/ Healthy.018	sqrt1-choiceSM Non dominant/ Non affected upper limb $p = 0.006$	sqrt1choiceRT Non dominant Contra-lateral lower limb/ Patients $p = 0.004$	sqrt1choiceSM Non dominant Contra-lateral lower limb $p = 0.021$	sqrt2-choiceRT Domina limb/ other/ Healthy $p = 0.003$ sqrt2-choiceRT Domina limb/ same/ Healthy $p = 0.035$
Data after reciprocal	rec1-choiceSM Non dominant/Non affected upper limb / Healthy.002 rec1-choiceRTNon dominant/Non affected upper limb / Healthy 4.00 ./ Patients 500	rec1-choiceSM Non dominant/ Non affected. upper limb $p = 0.050$ rec1-choiceRT Non dominant/ Non affected upper limb $p = 0.003$		rec1choiceSM Dominant Ipsi-lateral lower limb $p = 0.040$	

Table 26: Summary table of violations in normality and homogeneity of variance.

	1-choice RT-SM-UP.L		2-choice RT-SM-UP.L	
	Normality	**Homogeneity of variance**	**Normality**	**Homogeneity of variance**
All data including outliers	1-choiceRT Non dominant/Non affected upper limb/Healthy p =0.030	1-choiceRT Non dominant/ Non affected upper limb p =0.050	2-choiceRT Dominant/ Affected upper limb/ same side/ Healthy p =0.022 2-choiceRT Dominant/ Affected upper limb/ other side/ Healthy p = 0.001	
Data excluding	1-choiceRT Non dominant/Non affected upper limb/ Healthy p =0.006	1-choiceRT Non dominant/ Non affected upper limb. p =0.003	2-choiceRT Dominant/ Affected upper limb/ other side /Healthy p =0.035 2-choiceRT Dominant/ Affected upper limb/ same side /Patients p =0.047	
Data after log transformation	log1choiceRT Non dominant/Non affected upper limb/ Healthy p =0.015		log2-choiceRT Dominant/ Affected upper limb/ other side/ Patients p =0.002	
Data after square root	sqrt1-choiceRT Non dominant/Non affected upper limb/ Healthy p =0.018		sqrt2-choiceRT Dominant/ Affected upper limb/ other/ Healthy p =0 .003 sqrt2-choiceRT Dominant/ Affected upper limb/ same/ Healthy p =0.035	
Data after reciprocal	rec1-choiceRTNon dominant/Non affected upper limb / Healthy p =0.004 ./ Patients p =0.005	rec1-choiceRT Non dominant/ Non affected upper limb p =0.003		

Table 27: Summary table of violations in normality and homogeneity of variance after removing the SM variable.

4.3.2.3 Summary of checking the assumptions for the response time and speed of movement data

When all the data points were checked including the outliers, normality was violated in 10 variables (6 were SM) while homogeneity of variance was violated in 7 variables (6 were SM). After excluding the outliers in the SM, normality was found to be violated in 7 variables (3 were SM) and the homogeneity of variance was violated in 6 variables (5 were SM). Following the square root transformation, normality was violated in 4 variables only one of them was SM while the homogeneity of variance was violated in 3 variables (all SM). Finally after the reciprocal transformation, normality was also violated in 4 variables (3 were SM) and homogeneity of variance was violated in 2 variables (1 SM and 1 RT). (See Appendix 2/section 2.2, 2.4, 2.6, 2.8, 2.9 and 2.10 for a detailed assumptions check).

Normality violations are considered to be least serious and ANOVA is deemed to be robust under this violation (Zar 2010). On the other hand, the violations of homogeneity of variance especially in groups of unequal sizes should not be ignored as *F* might work in unpredictable ways (Lix *et al.* 1996). Therefore, the decision on which data set is selected out of the four mentioned above, needs to be done focusing on the homogeneity of variance findings. It is obvious that some homogeneity of variance violations were corrected after the transformation of data, as 3 violations were found after square root transformation and 2 after the reciprocal transformation. Taking a closer look at the homogeneity of variance in the transformed data, only one violation was found in the SM while in the reciprocal transformation there were two violations, one in SM and the other in RT.

The outliers that were excluded from the analysis were five in total, all were extremely fast scores of SM variable. SM was calculated from movement time (time from the release of the central pad till the end of movement) and the distance between the central pad and the target pad. Upon reflection on the protocol of data collection and the design of the kit, some issues are worth highlighting regarding the movement time. Although all participants were given the same standard instruction (once you see the light under the target pad, release from the central pad and hit the target pad as quickly as possible), it seems that different techniques were used while moving the hand or foot.

The required movement was to lift the hand/foot from the central pad and hit the target pad. When participants were seen to slide their hand/foot, the trials were repeated and they were told to avoid this type of movement. However, because of the fast speed of movement it is possible that some participants used sliding or other similar techniques without being recognised. There is also another concern regarding the movement time, as the distance were measured from the centre of the central pad to the centre of the target pad. However, the target pads were sensitive to any click on their surface, it is likely that some participants were touching the periphery or the edge of the target pad, as a result, this would be different than other participants who were aiming for the centre of the target pad. As a result of these issues around SM and the fact that violations in homogeneity of variance were mostly found in SM variables, SM data were not included in the analysis all together.

As seen in the summary table 21, the reciprocal transformation did not correct all the violations in homogeneity of variance in the response time variable; therefore, this transformed data will not be used in further analysis. However, both the log transformation and the square root transformation corrected all the violations in the homogeneity of variance in the response time variable, therefore, the transformed data could be used in further inferential statistics. Bearing in mind that the violations in the normality will be ignored as they are the least serious violation and they were only identified in two variables out of the total 10 response time variables. Furthermore, these abnormal distributions came from the same participants who had all the other variables normally distributed so will assume normality for these cases as well. As two different data transformations resulted in corrections of the homogeneity of variance, a decision must be made on which transformed data set will be used in further analysis. For this data set, the log transformed data is preferable over the square root transformed data because if we go back to the mathematical basis of the square root transformation, we will find that the square root of numbers above 1.00 become smaller, 1.00 and 0.00 remain constant and numbers between 0.00 and 1.00 become larger. The fact that numbers behave differently is noteworthy in data sets like the data in this study where there are a mix of values that fall between 0.00-1.00 and 1.00 and above because treating values differently will make the data more complex and difficult to interpret (Osborne 2002). Therefore, the log transformed data was used in further analysis.

Next is the mixed design ANOVA analysis of the log transformed RT data. It should be born in mind that the interpretations made out of the following analysis address the fact that log transformation affects the nature of the original raw RT data. Since the log transformation is classified as non linear transformation, spacing is not preserved between the data points, so inferences like twice as larger become irrelevant and cannot be used (Osborne 2002). However, if there is a value that is larger than another one in the original raw data, its logarithm is larger too, therefore, comments like smaller or larger are valid to be used when interpreting the analysed log transformed data.

4.3.2.4 Mixed Design ANOVA/ 1-choice RT in the upper and lower limb

There was no significant effect of the limb $F(1, 31) = 0.0004$, $r = 0.059$ indicating that response time of the upper and lower limbs were in general the same. Also there was no significant effect of the dominance/laterality $F(1, 31) = 0.109$, $r = 0.06$, which means that the response time of the dominant and non dominant limb in healthy participants were the same while patients with tennis elbow had the response time of their affected and non affected limb also the same. However, there was a significant interaction effect between the limb and dominance $F(1, 31) = 6.830$, $r = 0.42$. (See Appendix 1/ section 2.11 for the SPSS output of mixed design ANOVA). There was no significant effect of tennis elbow $F(1,31) <1$, $r = 0.04$. This indicates that the 1-choice response time of the upper and lower limbs from healthy participants and patients with tennis elbow were in general the same. Table 23 is a summary of the effect sizes and significance values for all the independent variables.

Variable	Effect size		Significance (p)
Tennis elbow	0.04	Negligible effect	Non significant
Limb	0.05	Negligible effect	Non significant
Dominance/Laterality	0.06	Negligible effect	Non significant
Limb x Tennis elbow	0.06	Negligible effect	Non significant
Dominance/Laterality x Tennis elbow	0.05	Negligible effect	Non significant
Limb x Dominance /Laterality	0.42	Medium effect	$P<0.05$
Limb x Dominance /Laterality x Tennis elbow	0.32	Medium effect	Non significant

Table 28: Effect size and p values for the 1-choice response time

Next the interaction effects are plotted using interaction graphs, these graphs are discussed in the light of significance values and effect size. The levels of the independent variables are shown in table 24.

Independent variables	Level	
Between participants independent variables	Healthy participants group	
	Patients with tennis elbow group	
Within participants independent variables	Limb (2 levels)	Upper Limb
		Lower Limb
	Dominance/ Laterality (2 levels)	Dominant upper/lower limb in healthy participants or affected upper limb/ipsi-lateral lower limb in patients
		Non dominant upper/lower limb in healthy participants or non affected upper limb/contra-lateral lower limb in patients

Table 29: levels of independent variables for 1-choice response time

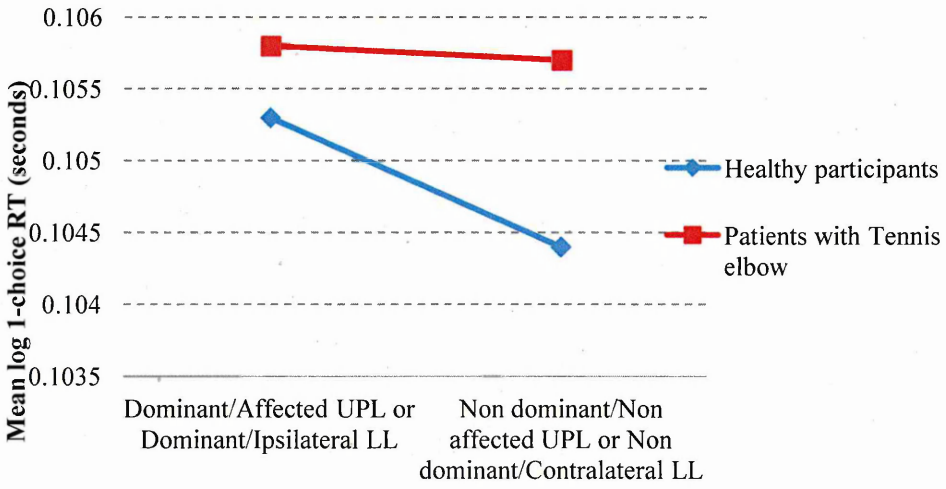

Figure 32: Interaction graph for Dominance x Tennis elbow

This interaction investigates if there is a difference between the 1-choice response time scores of healthy participants and patients with tennis elbow when they used their dominant/affected upper limb or ipsi-lateral lower limb as compared to their non dominant/non affected upper limb or contra-lateral lower limb. This interaction was not significant $F(1,31) = 0.087$, $p = 0.77$ and had less than small effect $r = 0.05$. However, the lines show that patients with tennis elbow had longer 1-choice RT which was almost the same whether they used their affected/ non affected upper limb or their ipsi-lateral/ contra-lateral lower limb. While healthy participants had shorter 1-choice RT and were faster when using their non dominant upper or lower limb.

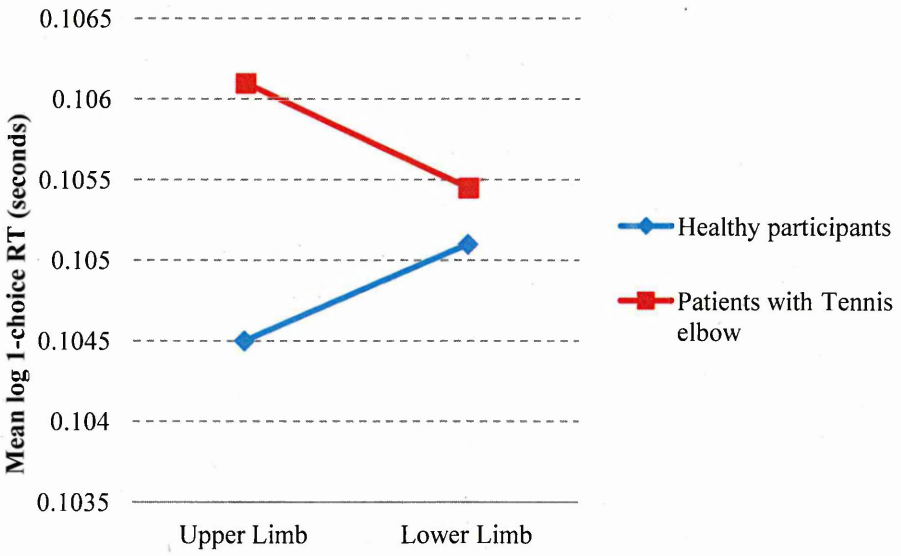

Figure 33: Interaction graph for Limb x Tennis elbow

The aim of the interaction illustrated in Figure 33 is to investigate if there is a difference between healthy participants and patients with tennis elbow when they used their upper limb as compared to their lower limb. This interaction was non significant $F(1,31) = 0.110$, $p = 0.742$ and it had less than small effect $r = 0.06$. However, the interaction lines are not quite parallel, which suggests that both groups were not the same when they used their upper limb as compared to their lower limb. Patients with tennis elbow had longer 1-choice RT when they used their upper limb as compared to their lower limb, while healthy participants showed the opposite as they had longer 1-choice RT when they used their lower limb as compared to their upper limb. This interaction graph also shows that patients had longer 1-choice RT as compared to the healthy participants in both upper and lower limbs.

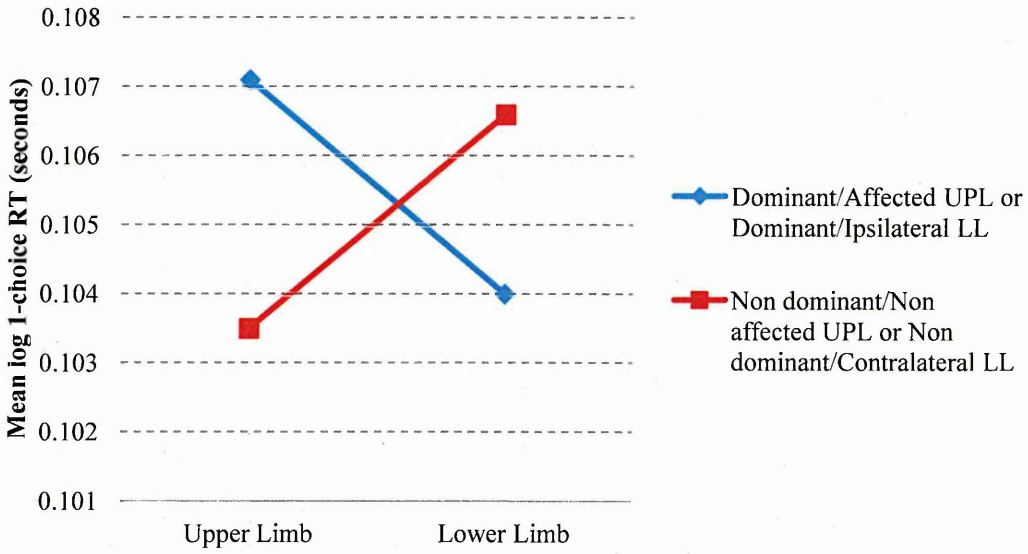

Figure 34: Interaction graph for Limbs x Dominance

The interaction graph in Figure 34 shows that the profile of 1-choice response time scores for the upper limb was different for dominant/ affected limb and non dominant/ non affected limb. The same applies for the 1-choice response time scores of the lower limb as it was different for the dominant/ ipsi-lateral and non dominant/ contra-lateral. The interaction here shows that participants achieved shorter response times when they used their non dominant/ non affected upper limb than when they used their dominant/ affected upper limb. While they achieved longer response times when they used their non dominant/ contra-lateral lower limb than when they used their dominant/ ipsi-lateral lower limb. The lines are intersected in this graph which indicates a strong interaction; this is also reflected in the statistical significance as the $p < 0.05$ and it has larger than medium effect size $r = 0.42$.

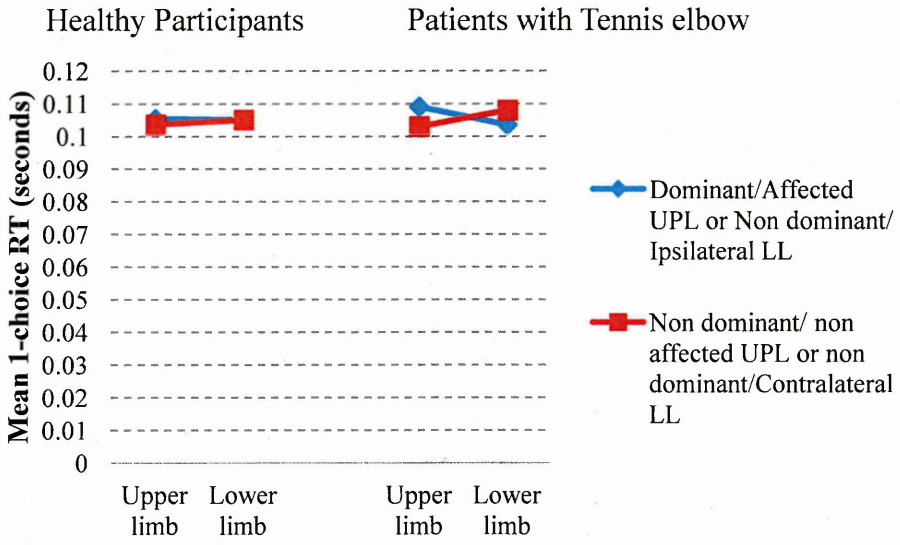

Figure 35: Interaction graph for Limb x Dominance x Tennis elbow

The aim of the three-way interaction illustrated in Figure 35 is to investigate the difference between dominance of the limb when healthy participants use their upper limb as compared to their lower limb and between upper and lower limb when patients with tennis elbow use their affected upper limb or ipsi-lateral lower limb as compared to their non affected upper limb or contra-lateral lower limb. This three way interaction was non significant $F(1,31) = 3.464$, *ns*, however, its p value approached significance at $p = 0.072$. It also had a medium effect size $r = 0.32$. It shows that healthy participants had longer 1-choice RT when they used their dominant upper or lower limb. For patients with tennis elbow, the intersecting lines indicates a strong interaction which might suggest that there is a difference between affected upper limb or ipsi-lateral lower limb as compared to the non affected upper limb or contra-lateral lower limb. Patients had longer 1-choice RT when they used their affected upper limb as compared to the non affected one. While they had longer 1-choice RT when the used their contra-lateral lower limb as compared to the ipsi-lateral one.

4.3.2.5 Mixed Design ANOVA/ 2-choice RT in the upper and lower limb

For the 2-choice response time there were three independent variables, two of these variables had no significant main effect. There was no significant effect of the limb $F(1, 31) = 0.120$, $r = 0.06$, indicating that the 2-choice response time of the upper and lower limbs were in general the same. Also there was no significant effect of the dominancy/affected $F(1, 31) = 0.595$, $r = 0.14$, which means that the 2-choice response time of the dominant and non dominant limb in healthy participants were the same while patients with tennis elbow had the response time of their affected and non affected limb also the same. However, there was a significant main effect of the target $F(1, 31) = 5.643$, $p < 0.05$. $r = 0.39$. The significant effect of the target tells us that if all the other variables were ignored, the 2-choice response time scores were different for the same side target as compared to the other side target as participants took more time when they had to hit the target on the other side of the tested limb. (See Appendix 2/ section 2.12 for SPSS output of mixed design ANOVA). There was no significant effect of tennis elbow $F(1,31) = 0.586$, $r = 0.14$. This indicates that the 2-choice response time of the upper and lower limbs from healthy participants and patients with tennis elbow were in general the same. Table 25 is a summary of the effect sizes and significance values for all the independent variables.

Variable	Effect size		Significance(p)
Tennis elbow	0.14	Small effect	Non significant
Limb	0.06	Negligible effect	Non significant
Dominance/ Laterality	0.14	Small effect	Non significant
Limb x Tennis elbow	0.28	Small effect	Non significant
Dominance/ Laterality x Tennis elbow	0.01	Negligible effect	Non significant
Limb x Dominance / Laterality	0.28	Small effect	Non significant
Limb x Dominance / Laterality x Tennis elbow	0.13	Small effect	Non significant
Target	0.39	Medium effect	$p<0.05$
Target x Tennis elbow	0.03	Negligible effect	Non significant
Limb x Target	0.06	Negligible effect	Non significant
Limb x Target x Tennis elbow	0.28	Small effect	Non significant
Dominance/Laterality x Target	0.15	Small effect	Non significant
Dominance Laterality x Target x Tennis elbow	0.17	Small effect	Non significant
Limb x Dominance /Laterality x Target	0.26	Small effect	Non significant
Limb x Dominance/Laterality x Target x Tennis elbow	0.1	Small effect	Non significant

Table 30: Effect size and p values for 2-choice response time.

Next the interaction effects are plotted using interaction graphs, these graphs are discussed in the light of significance values and effect size. The levels of the independent variables are shown in Table 26.

Independent variables	**Level**	
Between participants independent variables	Healthy participants group	
	Patients with tennis elbow group	
Within participants independent variables	Limb (2 levels)	Upper Limb
		Lower Limb
	Dominance/ Laterality (2 levels)	Dominant upper/lower limb in healthy participants or affected upper limb/ipsi-lateral lower limb in patients
		Non dominant upper/lower limb in healthy participants or non affected upper limb/contra-lateral lower limb in patients
	Target (2 levels)	Same side
		Other side

Table 31: Levels of independent variables for 2-choice response time.

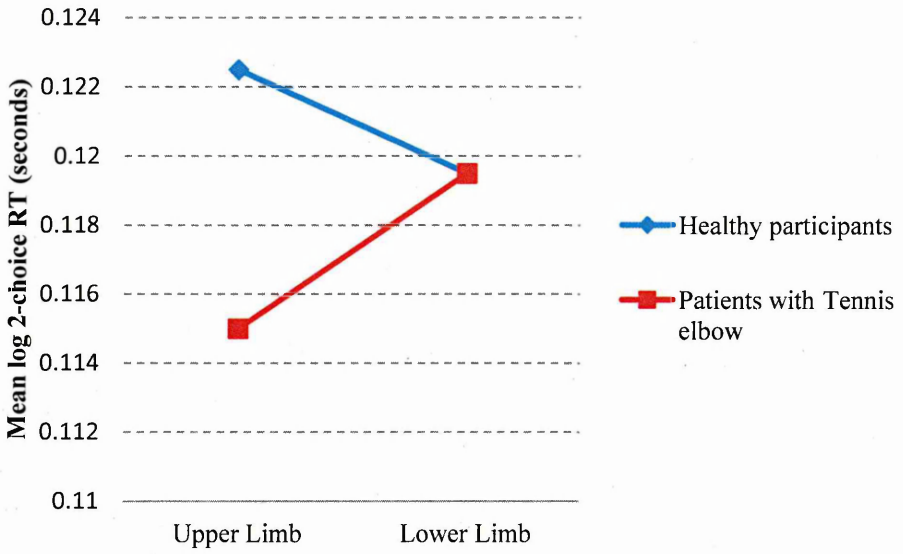

Figure 36: Interaction graph for Limb x Tennis elbow

The aim of the interaction illustrated in Figure 36 is to investigate if there is a difference between upper limb and lower limb in healthy participants as compared to patients with Tennis elbow. Although it was not statistically significant $F(1,31) = 2.723$, $p = 0.109$, it had about a medium effect size $r = 0.28$. The 2-choice RT of the lower limb was the same in both groups, however, the 2-choice RT of the upper limb was longer in healthy participants as compared to patients with tennis elbow.

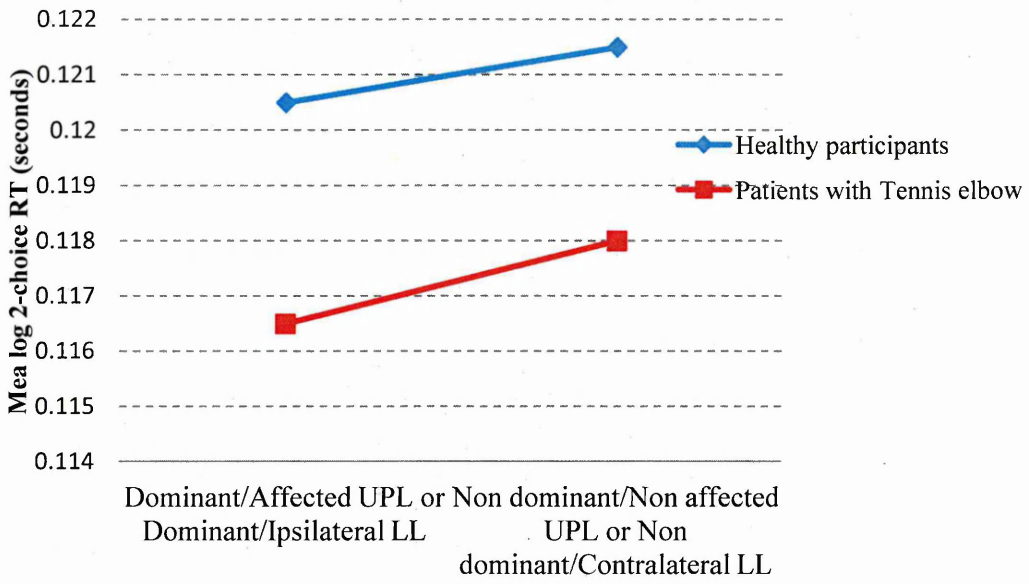

Figure 37: Interaction graph for Dominance x Tennis elbow

The aim of the interaction illustrated in Figure 37 is to investigate if the difference is the same between healthy participants and patients with tennis elbow when they use their dominant/affected UPL or ipsi-lateral LL as compared to their non dominant/non affected UPL or contra-lateral LL. This interaction was non significant, $F(1,31) = 0.004$, $p = 0.948$, and had a negligible size effect $r = 0.01$.

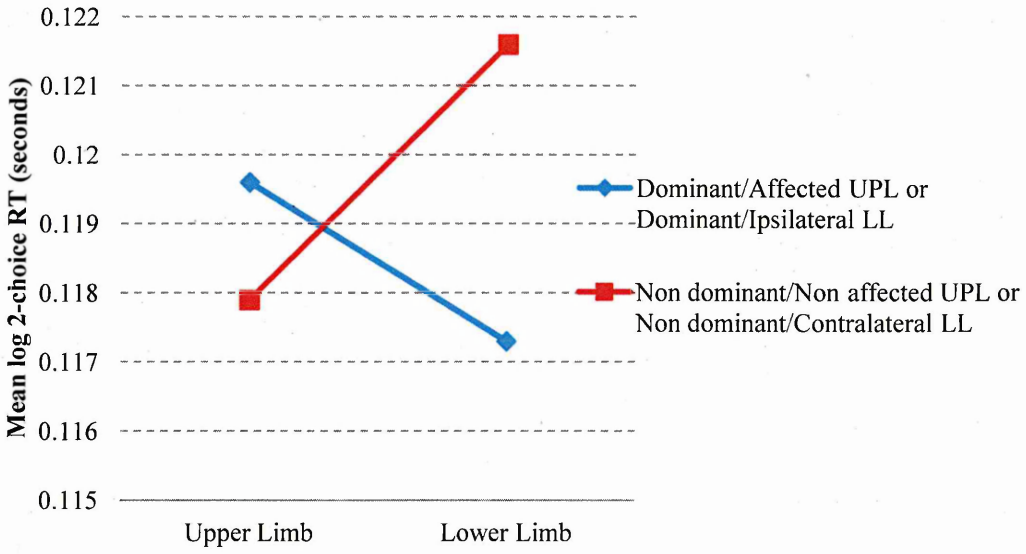

Figure 38: Interaction graph for Limb x Dominance/Laterality

The aim of the interaction illustrated in Figure 38 is to investigate if the difference between the upper limb and lower limb is the same when participants use their dominant/affected UPL or ipsi-lateral LL as compared to their non dominant/non affected UPL or contra-lateral LL. This interaction is statistically non significant, $F(1,31) = 2.640$, $p = 0.114$, but had about a medium size effect $r = 0.28$ that is shown by the intersecting lines. Different patterns could be identified here, as the non dominant/non affected UPL was faster than the non dominant/contra-lateral LL while the dominant/affected UPL was slower than the dominant/ ipsi-lateral LL.

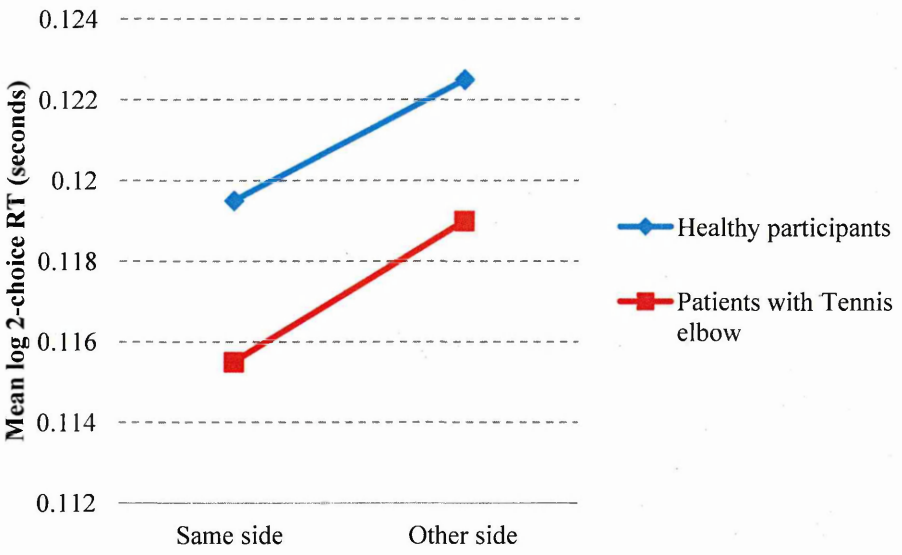

Figure 39: Interaction graph for Target x Tennis elbow

The aim of the interaction illustrated in Figure 39 is to investigate if the difference between 2-choice RT for target on the same side of the tested limb is the same for the target at the other side of the tested limb in healthy participants as compared to patients with tennis elbow. This interaction was not significant $F(1,31) = 0.028$, $p = 0.867$ and had negligible size effect $r < 0.1$. This interaction shows that both groups had the same pattern in 2-choice RT whether at the same side or other side target as participants tend to have longer 2-choice RT when the target was at the other side of the tested limb.

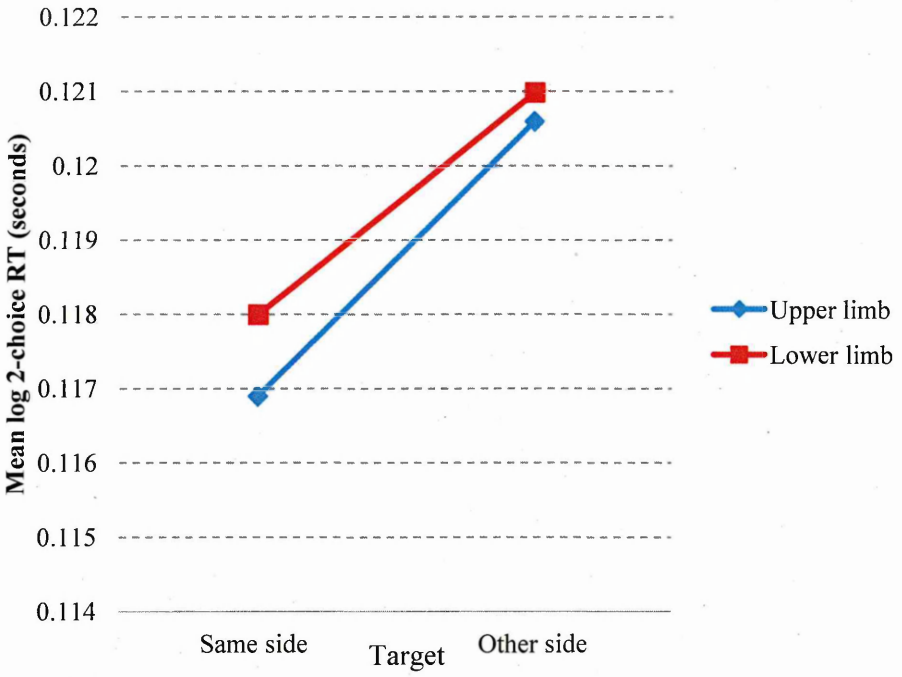

Figure 40: Interaction graph for Target x Limb

The aim of the interaction illustrated in Figure 40 is to investigate if the difference between 2-choice RT at the same side target is the same as the 2-choice RT at the other side target when comparing upper and lower limb. This interaction was not significant $F(1,31) = 0.103$, $p = 0.750$, and had less than small size effect, $r = 0.06$. The 2-choice RT was shorter when the target was at the same side of the tested upper and lower limb.

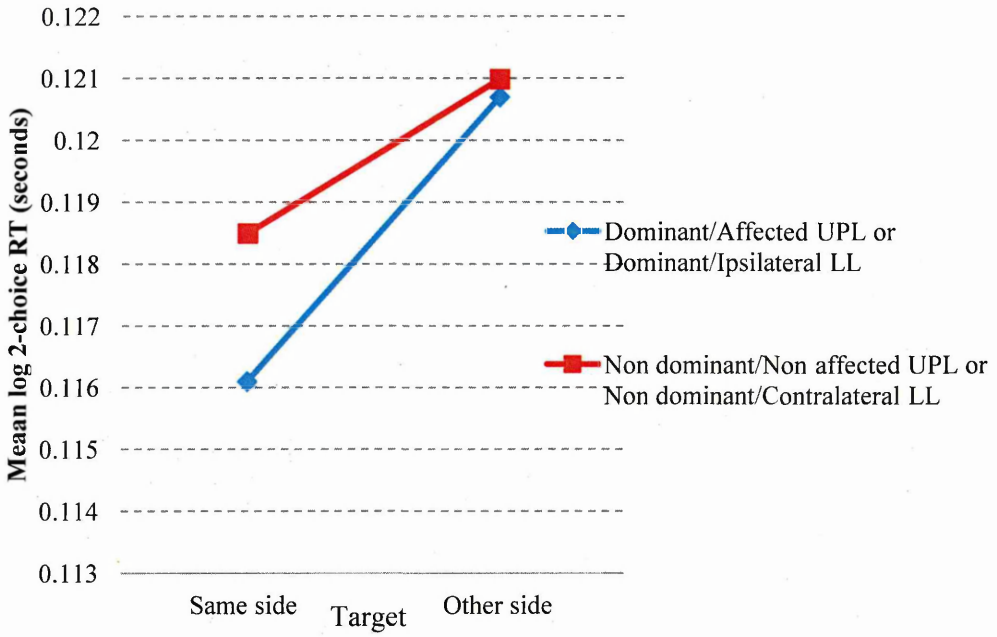

Figure 41: Interaction graph for Target x Dominance

The aim of the interaction illustrated in Figure 41 is to investigate if the difference between same side target is the same as for the other side target for the dominant/affected upper limb or dominant/ipsi-lateral lower limb as compared to the non dominant/non affected upper limb or non dominant/contra-lateral lower limb. This interaction was not significant $F(1,31) = 0.744$, $p = 0.395$, $r = 0.15$. This interaction shows that 2-choice RT for the same side target was shorter regardless of which limb used.

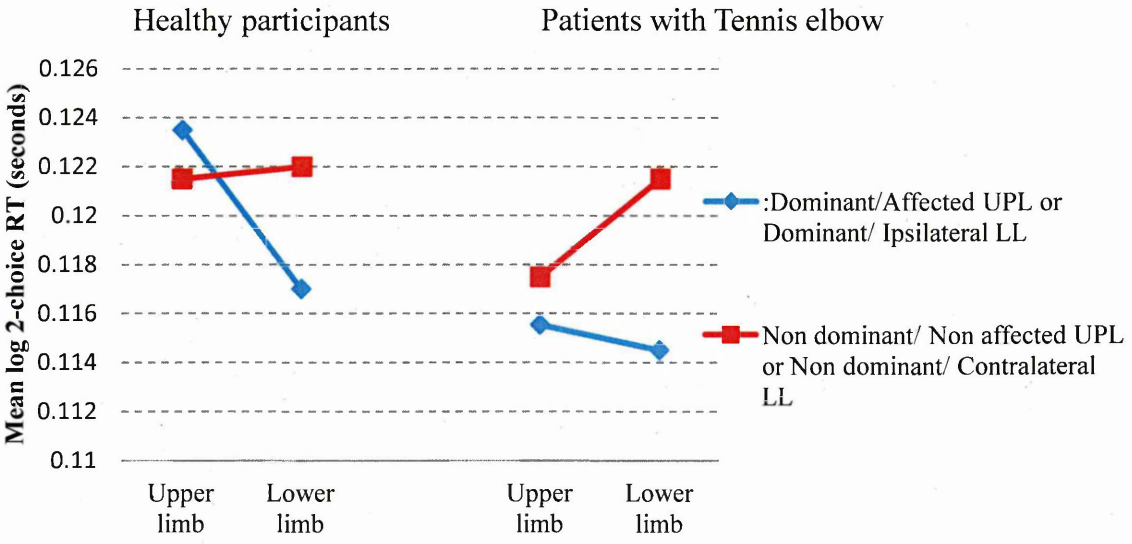

Figure 42: Interaction graph for Limb x Dominance x Tennis elbow

The aim of the interaction illustrated in Figure 42 is to investigate if the difference between dominant and non dominant limb was the same for upper and lower limb in healthy participants as compared to patients when they use their affected/ non affected upper limb or their ipsi-lateral/ contra-lateral lower limb. This interaction was not significant, $F(1,31) = 0.052$, $p = 0.822$ and had a small size effect $r = 0.13$. In each group there is an interaction between the upper/ lower limb and which limb is used. However, the pattern seen in healthy participants is different than the one seen in patients with tennis elbow. Healthy participants had a big difference in their dominant 2-choice RT when comparing upper and lower limb while their non dominant 2-choice RT was fairly similar in the upper and lower limb. While patients with tennis elbow had a noticeable difference between their upper and lower limb when they used their non affected upper limb or contra-lateral lower limb while the difference between upper and lower limb was less noticeable when they used their affected upper limb as compared to their ipsi-lateral lower limb.

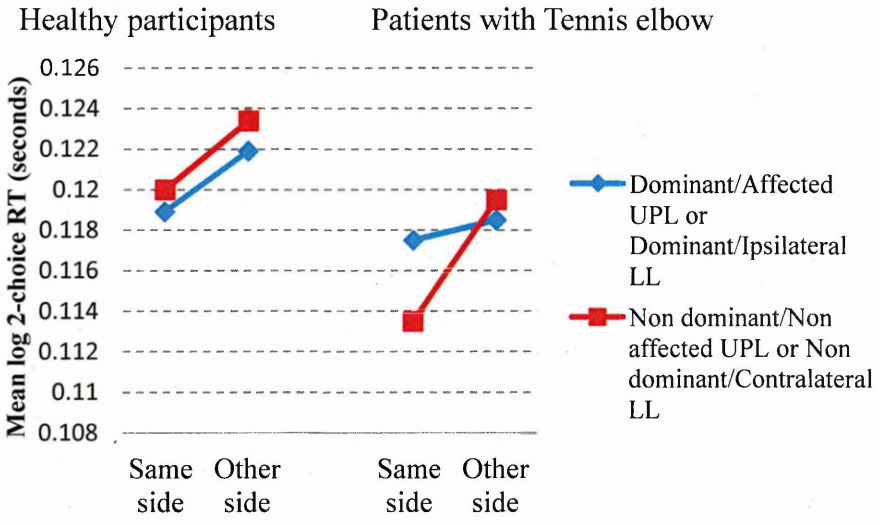

Figure 43: Interaction graph for Target x Dominance x Tennis elbow

The aim of the three-way interaction illustrated in Figure 43 is to investigate if the difference between the target on the same side of the tested limb and the target on the other side of the tested limb was the same in healthy participants as compared to patients with tennis elbow. This interaction was not significant $F(1,31) = 0.956$, $p = 0.336$ $r = 0.17$. Healthy participants displayed the same pattern of response whether the target was at the same side or the other side of their tested limb. However they had longer response time when they used their non dominant upper limb or lower limb. On the other hand, there was an interaction between the target and the tested limb in patients with tennis elbow. The affected upper limb or ipsi-lateral lower limb had a very similar response time whether the target was on the same side or the other side. While there was a clear difference between same side target and other side when patients used their non affected upper limb or contra-lateral lower limb, as patients had longer response time when the target was at the other side.

Chapter 5

Discussion

Chapter 5: Discussion

This chapter includes five main sections. The first section discusses the importance of acknowledging the relevance and meaningfulness of the statistical findings according to the clinical context. The second section discusses the findings of the balance test. The third section discusses the findings of the response time test. The fourth section is an overall discussion and the fifth section discusses and reflects on the limitations in this research. All the findings were interpreted and discussed in the light of their statistical significance, effect size, the interaction between different variables and their possible clinical and practical implications.

5.1 Statistical significance and clinical significance

Research findings in health science research are predominantly analysed using statistical tests of significance and physiotherapy research is no exception. However, there are inherent limitations in this approach starting from the type I error and type II error (Houle and Stump 2008; Mawson 2005; Kazdin 1999). Statistical significance tests are established probability measures of detecting change but they do not tell us the meaningfulness of the change (Kazis *et al.* 1989). On the other hand, it should be born in mind that the 0.05 is just a threshold number. Therefore, non significant values that approach 0.05 should not be discarded all together; they should be interpreted in their context instead. Another issue to be highlighted is that the end result of the statistical significance is divided into either yes or no, whereas clinical findings are by definition not dichotomous (Houle and Stump 2008).

The interpretations of the statistical significance tests and drawing conclusion based on the arbitrary number of 0.05 have been always a debate among researchers (Sterne and Smith 2001). However, different disciplines show different ways of dealing with the statistical findings according to the aim of these disciplines. Sport research is an example where small changes could mean a lot when talking about the incremental changes that would take the human performance to the next level. On the other hand,

researchers in health tend to be more conservative when it comes to recognising small changes or non significant values. Yet, health research covers a wide range of different clinical studies. A conservative approach is warranted in phase III clinical drug trials for example but that is not necessarily the case in evaluation and exploratory studies (Cannistra 2009).

Supporting this argument, Cannistra, (2009) proposed setting the *p* value higher than the 0.05 in exploratory small sample studies aimed at generating hypothesis. Where the results are expected to be statistically non significant but might be clinically promising. He recommended setting the *p* value at 0.1 as the findings of these studies are not definitive and need be validated in further research with larger sample size. Despite the fact that his recommendations were aimed at phase II randomised controlled trials, his debate and recommendations also apply to any clinical exploratory study. As a result, the type I error is high but this false positive result is acceptable according to the reasons mentioned earlier.

Reflecting on the issues around statistical significance and in order to help researchers determine the meaningfulness and usefulness of their data, the concept of clinical significance has been used in conjunction with statistical significance results. Clinical significance could be simply defined as the practical importance of the effect being investigated (Kazdin 1999). Clinical significance has been largely discussed in relation to the effectiveness of treatment. However the use of this concept is by no means less important in exploratory studies that investigate assessment techniques as well, because an effective treatment plan is based on the findings of the clinical assessment in the first place (Kazdin 1999). Given that this research was an exploratory study assessing the sensorimotor function in patients with chronic tennis elbow. The meaningfulness of the statistical significance findings will be discussed in the light of the multi-structural pathology of the condition and possible implications for its clinical management.

As discussed earlier, the clinical significance refers to the meaningfulness of the findings which might vary between the clinicians, patients, commissioners and policy makers. Therefore, the term "clinical" in clinical significance could be variably defined according to the target audience (Guyatt *et al.* 2002). Researchers should be clear about

their target audience as this will determine the way they make their findings comprehensible to this particular audience (Guyatt *et al.* 2002). As an exploratory study, the dissemination of the research findings presented in this thesis will be mainly targeting health professionals involved in the management of tennis elbow. However, as the merit of rehabilitation is to deliver a patient centred care, it could be argued that the meaningfulness perceived by health professionals and patients will be reasonably related.

It is important to recognise that clinical significance is established in some areas more than others. Psychology research addressed the importance of clinical significance since the 1980s, the concept and mathematics of clinical significance have been studied and discussed in depth and indexes were developed (Jacobson *et al.* 1999). The use of clinical significance in physiotherapy is not as systematic as it is in psychology. As a result, the clinical significance could be determined by the effect size (Kazis *et al.* 1989) and the researcher's clinical reasoning. The latter could be criticised as subjective, however, this does not mean that the process is random. Dr. Naratomi Houston (1977)[11] once said "with my eyeballs alone, I can see this clinically significant". This quote emphasises the crucial role of the researcher's own judgment of the observed change or effect.

It is noteworthy to mention that the Bayesian interpretation of confidence intervals has been suggested to be used as an alternative to *p* values in situations where the results are statistically non significant but large enough to be clinically relevant as in small sample size (Bruton *et al.* 1998). However, this approach could not be used in this research because it depends on setting a prior distribution for the results which is not applicable in this study as it is the first one to assess balance and response time in the lower limb. Another limitation in the Bayesian method is the sensitivity of the uniformity to transformation (Burton *et al.* 1998). Given that the response time data in this study was analysed after log transformation, the Bayesian approach is not valid to be used here.

In the light of the previous discussion, the *p* value in this research was set at 0.05. However, this exploratory research aims to generate hypothesis that might help

[11] Cited in (Houle and Stump 2008).

clinicians to modify their management approach of chronic tennis elbow and consequently improve the patient's quality of care. Bearing in mind the novelty of this research and the small sample size, non significant findings that approached significance and had medium effect size will be discussed as the benefits of addressing these possible effects overweigh the loss of information that is possibly hidden by the non significance value. Yet, it is to be remembered that the findings are not definitive and requires further studies with larger sample size.

5.2 Discussion of the balance test findings

This is the first study to investigate generalised sensorimotor function in patients with chronic tennis elbow by measuring balance and response time of the lower limb. Previous studies suggested a central sensitisation process in patients with tennis elbow and speculated generalised sensorimotor deficits in these patients (Pienimakie *et al.* 1997, Bisset *et al.* 2006 and Bisset *et al.* 2009). However, bilateral assessment of the upper limb was the main focus of the research on tennis elbow so far. The research undertaken of this PhD program was also inspired by clinical observations reported by experts in chronic tennis elbow management at the Host organisation. Clinicians there noticed that patients with chronic tennis elbow tend to have poor balance when asked to stand on one leg. One aspect of sensorimotor function investigated in this research was the postural control during single leg standing. TtB was the outcome measure chosen to assess the postural control because it captures spatial and temporal characteristics of postural control (Haddad *et al.* 2006). TtB was reviewed in detail in the literature review chapter under section (1.2.5.4) and in the methods chapter under section (2.4.1.4).

Patients with chronic tennis elbow showed lower TtB ap compared to the healthy controls. This indicates that while patients were controlling their balance on one leg, their postural control system was functioning by placing their COP nearer in time to the stability limit, which makes them more prone to postural control instability as compared to the healthy controls. Similar findings of lower TtB were reported in patients with unilateral chronic ankle instability (Hertel and Olmsted-Kramer 2007). The authors suggested that this could be caused by alterations to the postural control system mechanism of controlling the neuromuscular function of the lower limb. Authors also highlighted the growing evidence of central neuromuscular involvement in unilateral joint injuries.

Another possible explanation for the lower TtB ap values in patients with tennis elbow could be that these patients had poor postural control before they developed tennis elbow. This suggestion remains a possibility that is very difficult to verify because it needs longitudinal studies that investigate postural control before and after tennis elbow. This implies that a sample should include people who are expected to have tennis elbow. Given that the aetiology of tennis elbow is still not clearly understood, this hypothetical sample is very difficult to be identified. However, novice tennis players are at high risk of developing tennis elbow as 50% of these players will develop the condition (Nirschl 1986). Therefore, a target group of novice tennis players is expected to include individuals who might develop tennis elbow at some point. However, only 10-15% of patients diagnosed with tennis elbow are tennis players, which means that a target sample of tennis players will not be representative to the majority of patients with tennis elbow. In addition to this, longitudinal studies are time consuming and costly, the concerns identified with this design overweigh the benefits of running such a research.

Unlike TtB ap, results showed that TtB in the ml direction was not statistically significant and had less than small effect size, which implies that participants from both groups were in general the same in their medio-lateral stability. The most plausible explanation for differences in the TtB ap and ml could be due to the different mechanisms of controlling the COP. In the double stance, the maintenance of the

postural control is attributed to the hip and ankle strategies as the COP is controlled by the ankle dorsi-flexors and planter-flexors in the ap direction while it is controlled by the hip abductors and adductors in the ml direction (Winter 2005). Shumway-Cook and Woollacott (2011) also suggested that the hip and trunk are primarily used to recover the medio-lateral stability during double stance in healthy individuals and the recovery strategy works in a proximal to distal fashion. However, the postural control strategies described in the double stance have not been investigated in single leg standing. Nevertheless, a study by Gribble and Hetrel (2004) showed that fatigue of the hip abductors and adductors resulted in postural control deficits while fatigue of the ankle evertors and invertors did not during single leg standing. The postural control deficits reported in Gribble and Hertel's study were observed in the frontal plane not the sagittal plane which suggests that the hip abductors and adductors have a significant role in the maintenance of medio-lateral stability in single leg standing. The reason why patients with chronic tennis elbow had their TtB ap more affected than TtB ml as compared to the healthy participants needs to be further investigated.

Within group effects will be discussed next and the patterns showed by both groups will be compared as this might provide new insight into different characteristics between the groups. The first within group variable to be discussed is the visual condition. Results showed that the effect of the visual condition on TtB ap and ml was substantially significant and had a large size effect in both groups. This finding is not surprising and it is in line with the study by van Wegen *et al.* (2002). Vision is one of the vital sensory inputs used by the postural control system to maintain the balance. Both groups exhibited the same pattern of TtB ap and ml in the different eyes conditions. However, patients with tennis elbow had shorter TtB ap and ml than healthy participants in both visual conditions.

The second within group variable was the stance limb, whether it was the dominant/ non dominant in healthy participants or ipsi-lateral/ contra-lateral lower limb in patients with tennis elbow. This was statistically significant in the TtB ap as longer TtB were recorded when participants stood on their non dominant or contra-lateral lower limb. This means that participants were showing more postural instability when

they stood on their dominant or ipsi-lateral lower limb which was the right lower limb[13]. It is noteworthy to mention here that the dominancy of the lower limb or footedness was determined by subjective leg preference as participants were asked which lower limb they use to kick a ball. Obviously their answer will be regarding the kicking lower limb not the stance one. In other words, the dominance of the lower limb was determined according to a mobility function while the function of concern in the balance test is stability. However, determining the dominance of the lower limb has always been a debatable issue (Gabbard and Hart 1996). Even for the ball-kick test, controversy exists whether to deem the stance leg or the kicking leg as the dominant leg. In the same quest, Maki (1990) reported in his PhD dissertation that the foot preference for kicking activity based on the mobile leg was not the same for foot preference in uni-pedal stability like the single stance test.

Regardless of the method used to classify the leg dominance, the significant main effect of the stance leg in this study challenges the findings of Hoffman *et al.* (1998) who found no differences in the postural control between the dominant and non dominant leg in healthy individuals. Postural control measures in Hoffman *et al's.* study were sway path length and sway area while the dominance of leg was defined as functional leg dominance. The latter was determined by doing a battery of functional tests, these included a ball kick test, step up and balance recovery. On the other hand, the significant longer TtB of the non dominant lower limb of stance limb shown in the research presented in this thesis agrees with the suggestion made by Previc (1991). In his general theory concerning the prenatal origins of cerebral lateralisation in humans, the principles of the theory predict that in a unilateral stabilising context, the reliance will be on the left foot to maintain postural control due to the greater antigravity extension exhibited on that side. The greater antigravity extension on the left side originates from the predominance of the left vestibular organ and its neural pathways which in turn result in stronger vestibulospinal reflexes (Previc, 1991).

To further highlight the issue of functional lateralisation, evidence comes from the literature on children development. In the stepping reflex, children were found to

[13] All healthy participants reported that their right leg was the preferred or dominant leg. All the patients with tennis elbow had their right elbow as the affected one so the ipsi-lateral leg was the right one.

lead with their right foot (Peters and Petrie 1979). This bias reflects the preference of right foot in actions while the left foot is used for support. Although this evidence is not well established, as other similar studies did not yield reliable right foot biases in the stepping reflex, it highlights the effect of early motor development on the future leg preference.

Another insight into the link between foot preference and function was presented by Peters (1988). In his extensive review, he concluded that the right handed adults prefer to use their right foot in activities that requires manipulation and attention while the left foot provides the support. He based his conclusions on anatomical asymmetries between the both lower limbs as the left leg tend to be heavier and longer in right handed adults. This anatomical asymmetry could also help to explain why participants in this study showed more stability when standing on their left foot. It could be that the heavier weight of the left leg puts it in an advantageous position when it comes to stabilising on one leg compared to the right leg. As one could expect that more sway will be needed to induce instability in the heavier leg.

Patients with tennis elbow had shorter TtB ap and TtB ml when standing on their ipsi-lateral lower limb as compared to their contra-lateral lower limb. For all the patients the ipsi-lateral lower limb was their dominant one which was the right foot. Similar to the discussion presented in the previous paragraph, these differences between the two limbs could be the result of the preference of the left foot in stabilising activities (Previc, 1991). However, as patients had shorter TtB ap than the healthy participants, a possible effect of tennis elbow on the postural stability in the anterio-posterior direction was suggested but it warrants further investigation. Therefore, it is not known whether the differences between the two lower limbs in these patients are linked to the affected side of tennis elbow or not.

In the TtB ml, the interaction between the stance limb and group (healthy participants and patients with tennis elbow) approached significance at $p = 0.08$ with a medium size effect. This indicates that patients with tennis elbow had a noticeable different pattern of TtB ml during standing on their ipsi-lateral or contra-lateral lower limb than the healthy controls when they stood on their dominant or non dominant lower limb. It is of interest to recall that the medio-lateral stability was in general the

same between the two groups. However this interaction tells us that although the TtB ml did not differ between the groups, patients with tennis elbow had a different pattern of TtB ml than the healthy controls when comparing the stance limb. This might indicate that patients with chronic tennis elbow have developed a new strategy for controlling their medio-lateral stability. As discussed earlier, it has been suggested that the proximal musculature of the hip plays a significant role in maintaining the postural control in the ml direction during single leg standing in healthy participants (Gribble and Hertel 2004). However, strategies of balance recovery were not investigated here as they are out of the scope of this thesis and they warrant further investigation in future research.

The findings of the postural control in patients with chronic tennis elbow are preliminary and remain non conclusive. Therefore, further research investigating the postural control in these patients is warranted with larger sample sizes.

5.3 Discussion of the response time findings

The response time test included two outcome measures; the RT and the SM. However, the SM data was not included in the final analysis because some variables were non homogeneous and there were some issues in the data collection and the equipment design. These issues were discussed in detail in the data analysis chapter under section 4.3.2.3. Therefore, this section will discuss the findings of the response time data. The protocol for the response time test was designed to replicate what has been done previously by Pienimaki *et al.* (1997); Bisset *et al.* (2006) and Bisset *et al.* (2009). The equipment used in the response time measurements was designed by the Centre for Sports Engineering Research at Sheffield Hallam University and was made as similar as possible to the equipment used in the previous studies identified earlier.

5.3.1 One-choice response time

There was no significant difference in the 1-choice RT between patients with chronic tennis elbow and healthy participants. This finding contradicts with the previous findings by Pienimakie *et al.* (1997); Bisset *et al.* (2006) and Bisset *et al.* (2009). All the previous studies reported significant differences in the 1-choice RT between patients with chronic tennis elbow and healthy controls. Similar to the previous studies, this

research targeted chronic patients with tennis elbow. Furthermore, the protocol of data collection in this research was the same as the previous studies but the equipment used to assess the response time was different. The basic design of the equipment used in this study is similar to the PEB module which was used previously. However, the equipment in this study was designed to measure RT of both the upper and lower limbs and it is smaller in size. Therefore, a plausible explanation for these differences in findings is the different equipment used for data collection or different patient population.

The interaction between the limb and the side (limb x side) was statistically significant and had a medium size effect. Participants from both groups achieved shorter response times when they used their non dominant/ non affected upper limb than when they used their dominant/ affected upper limb. While they achieved longer response times when they used their non dominant/ contra-lateral lower limb than when they used their dominant/ ipsi-lateral lower limb. The impact of this significant interaction is clarified in the following paragraph.

Another statistically significant finding was the three-way interaction (Limb x side x group). It showed that healthy participants had longer 1-choice RT when they used their dominant upper limb. This finding disagrees with the previous literature where the dominant upper limb of healthy participants showed shorter RT and faster SM (Pienimaki *et al.* 1997 and Bisset *et al.* 2006). For patients with tennis elbow, longer 1-choice RT were recorded when they used their affected upper limb as compared to the non affected one, this is in line with the previous findings of Pienimaki *et al.* (1997); Bisset *et al.* (2006) and Bisset *et al.* (2009). With regard to the lower limb, healthy participants had shorter RT with their dominant foot. This brings us back to the issue of foot dominancy discussed earlier under the balance test findings, to recall, the right lower limb is favoured in mobility functions. Patients with tennis elbow had longer 1-choice RT when they used their contra-lateral lower limb as compared to the ipsi-lateral one. Given that the contra-lateral limb was the left foot in these patients, again we could infer that the right foot is preferred for mobility functions. However, bearing in mind those patients had slightly longer 1-choice RT than healthy participants, sensorimotor changes were suggested but this warrants further investigation.

5.3.2 Two-choice response time

There was no significant effect of tennis elbow. This indicates that the 2-choice RT of the upper and lower limbs from healthy participants and patients with tennis elbow were in general the same. This opposes the results of the previously mentioned studies where significant differences in the 2-choice RT between patients with chronic tennis elbow and controls. However, similar to the discussion in the 1-choice RT, the issues around the equipment used in collecting the data for this study should be born in mind.

The findings of the 2-choice RT disagree with the 1-choice RT as patients with tennis elbow recorded shorter RT than healthy participants. It is important to clarify that the original instruction was to release from the central pad and hit the target pad, thus two different times were measured, the RT and the movement time (MT), the latter was used to calculate the SM. As explained in detail earlier, the SM was not included in the final analysis. A possible explanation could be that patients with tennis elbow were very competitive in this task as it involves more complexity than the 1-choice RT and therefore did better than the healthy participants. However, the fact that the findings of all the other outcome measures included in this research were consistent in the way that the sensorimotor function of patients with tennis elbow was affected compared to the healthy participants, therefore, the contradicting findings of the 2-choice RT should not be misleading and might be due to the factors discussed earlier.

There was a significant main effect of the target; this tells us that if all the other variables were ignored, the 2-choice RT was shorter for the same side target as compared to the other side target. Participants took more time to respond when they had to hit the target on the other side of the tested limb. Participants were seated facing the central plate in the middle so the tested limb has to cross the body's midline if the target was at the other side (See Figure 44).

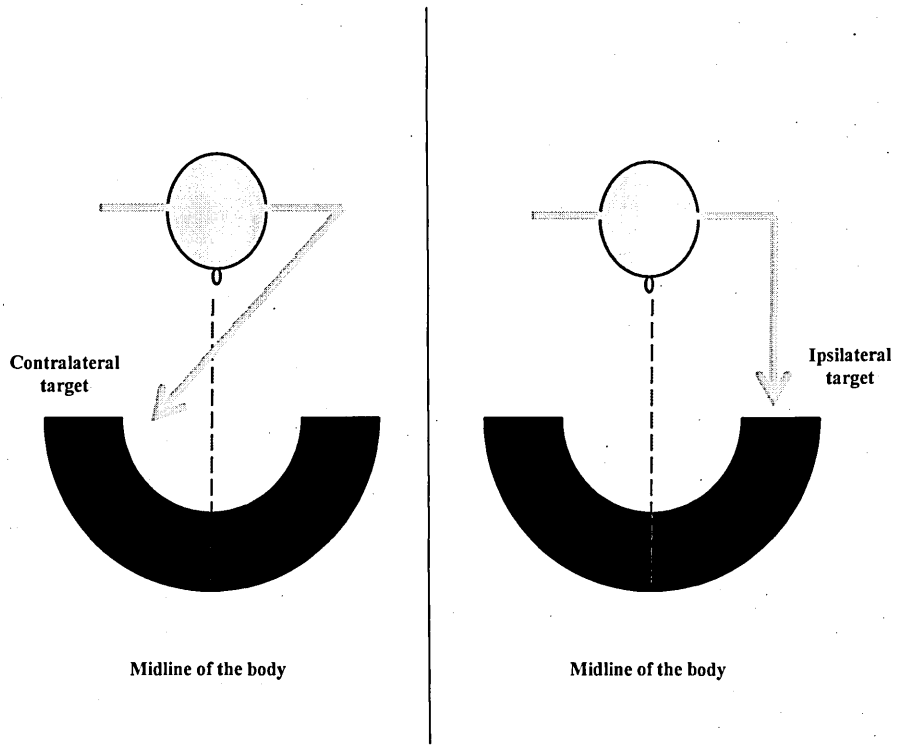

Figure 44: A schematic diagram of the hand movements toward ipsi-lateral and contra-lateral visual targets.

Previous research investigating reaching movements to ipsi-lateral or contra-lateral visual targets reported shorter reaction time, shorter movement duration and higher peak velocity when the movement was aimed to the target at the same side of the reaching limb. Neurological and biomechanical hypotheses were suggested to explain the differences in response toward ipsi-lateral and contra-lateral targets. A neurological hypothesis is based on the intra-hemispheric processing which is suggested to be more efficient when transmitting visuo-motor information of the target at the ipsi-lateral side of the reaching limb (Fisk and Goodale 1985). Another possible explanation suggested by the neurological hypothesis is that the motor output might be better executed in situations that do not involve crossing the midline of the body. On the other hand, the biomechanical model hypothesises that inertial loads depends on the perpendicularity of the hand movement in relation to the axis of the upper limb. As hand movements perpendicular to the upper limb axis will have higher inertial loads than hand movements parallel to the upper limb axis (Gordon *et al.* 1994). Reflecting on the movements in the study presented in this thesis, hand movements aimed at the contra-

lateral visual target are more perpendicular to the upper limb axis as compared to the hand movements aimed at the ipsi-lateral target.

5.4 Overall discussion

This is the first study that investigated general sensorimotor deficits in patients with chronic tennis elbow as compared to healthy participants. Although the group differences in the balance and response time tests were not statistically significant, TtB ap approached significance and had a medium size effect. Patients with tennis elbow were prone to more postural instability than the healthy participants as they had shorter TtB ap and TtB ml. The patients group also were slower to respond in the 1-choice RT test. These findings suggest that patients with tennis elbow show signs of sensorimotor deficits, however, these findings are not conclusive and further research with larger sample size is warranted.

This exploratory study provided new evidence in the field of sensorimotor function in patients with chronic tennis elbow as the findings of the postural control investigations suggest that sensorimotor deficits might extend to the lower limbs in these patients. However, it is too early to discuss the implication of these findings as we need to determine the extent and the clinical relevance of possible sensorimotor deficits in the lower limb. Although bilateral sensorimotor deficits in the upper limb have been reported in previous studies (Pienimaki *et al.* 1997, Bisset *et al.* 2006 and Bisset *et al.* 2009), their extent and clinical relevance were not further investigated. It is important to clarify the clinical implication of sensorimotor deficits as the treatment approaches for tennis elbow are variable with conflicting evidence and questioned long term effectiveness (Wood *et al.* 2006). Current physiotherapy management of tennis elbow does not involve any sensorimotor training. Future research on tennis elbow should consider investigating the effectiveness of sensorimotor training in these patients as compared to other methods.

Bilateral sensorimotor changes have been also reported in other musculoskeletal conditions such as the anterior cruciate ligament injury of the knee (Ageberg 2002). The reason for the postural instability in the ap direction as shown in the findings of the research presented in this thesis is not clearly understood yet. However, a number of

theories have been proposed in an attempt to explain the bilateral sensorimotor changes in patients with chronic tennis elbow that were reported in previous studies (Pieninmaki *et al.* 1997; Bisset *et al.* 2006; Bisset *et al.* 2009). One theory hypothesises cerebral inter-hemispheric communication; this crossed interaction might result in an information transfer between the hemispheres (Bonato *et al.* 1996; Stinear *et al.* 2001). This process might lead to mapping the impaired motor task of the affected limb into the non affected side which is then manifested as bilateral changes.

Another theory suggested to explain the bilateral changes is linked to the central neuromotor processing as the persistent pain could be responsible of altering the muscle activation mechanism and reorganisation in the somatosensory cortex (Flor *et al.* 1997). This process is hypothesised to be triggered by the effect of pain on altering the movement pattern of the upper limb. This will lead to faulty proprioceptive input which in turn will cause disruption to the internal body representation in the brain (McCormick *et al.* 2007). The disrupted imagery in the brain will make the sensory input not compatible with the motor output which could be detected as sensorimotor deficits (McCabe *et al.* 2005). These theories remain hypothetical and warrant further research in patients with chronic tennis elbow. Future research should incorporate transcranial imaging to investigate the existence of any cortical reorganisation involvement in these patients.

Theories proposed to explain bilateral changes are based on the concept of brain plasticity, which could be simply defined as a dynamic characteristic of the brain that enables the brain to reorganise its structure and function based on sensory input, learning or following injury (Duffau 2006). However evidence shows that patients with chronic pain undergo changes in their cortical representation of the affected part of the body and other structures that have afferent and efferent connections with the affected part, this explains changes seen on the opposite intact motor cortex (Rothwell 2010). A study involving patients with chronic back pain of mechanical origin showed significant increase of cortical activity accompanied by enlarged cortical presentation of the affected back area. Authors suggested that this might be responsible of the persistent pain experience in these patients (Flor *et al.* 1997). Given the chronicity of tennis elbow reported by the patients involved in this research, cortical changes is expected to be

found in these patients similar to the evidence presented in the chronic back pain. Although all the theories discussed here were proposed to explain the bilateral sensorimotor changes in the upper limb in patients with tennis elbow, their principles could be extended to explain the general sensorimotor changes as seen in the increased postural instability in these patients.

5.5 Limitations

This research had some limitations that were addressed in different places throughout this thesis. This section aims to highlight these limitations and reflect on their implications on the findings of this research and recommendations for future research.

The response time test in this study was meant to replicate the previous studies of Pienimaki *et al* (1997); Bisset *et al.* (2006) and Bisset *et al.* (2009) to allow for the findings to be compared. Therefore, the same protocol was followed and the equipment was made to be similar to the PEB module that was used in previous studies. However, there are some differences between the equipments used to measure the RT and MT. The PEB manufacturer produces two separate modules for the upper and lower limb but the equipment used in this study was designed to be used for the upper and lower limb. The equipment used in this study is smaller in size than the PEB-1, the board, the pads and the lights are smaller in size. These differences in the design could have resulted in the differences between the findings of this study and the other studies. Future research using the equipment used in this study should consider alterations in the design and size of the equipment.

The SM data was not included in the final analysis due to a number of issues in the data collection. All the participants were given the same instruction as: "when the light under the target pad is on, release form the central pad and hit the target pad". It was noticed that some participants slide their hands or pivoted them at the target pad and hit with their fingers instead of lifting the hand and moving toward the target pad. The target pads were very sensitive; a fine click anywhere on the pad would be enough for the time to be recorded. Therefore, participants hitting the centre of the pad would have a longer MT than those hitting the edge of the pad. These different techniques

resulted in extremely fast MT which would have biased the findings if the SM was included in the analysis. The instruction given to the participants should have been more specific in terms of where to hit the pad exactly. Another option would be marking an area on the pad so the hits would be more consistent between participants.

Another limitation was the sample size of the patient group which is relatively small compared to the previous studies. This might have resulted in the differences between the current findings and other studies. However, the issue about the number of patients in this study need to be addressed according to the following factors. Patients were first recruited from the Host organisation as the acute hospitals are the final referral for patients with chronic tennis elbow after the failure of community based conservative treatment. However, the number of patients with chronic tennis elbow referred to the orthopaedic department was lower than expected when compared to the number of referral over the previous years. This was a result of retaining patients in the primary care trust (PCT) instead of referring them to the Host organisation. To increase the number of the patients in this study, the ethical approval and clinical governance were extended to include the PCT. Considering this late change and the time constraints of this research program, a larger sample size of patients would have been very difficult to obtain.

The reliability of the tested measures used in this research was assessed in two reliability studies presented in chapter 3. However, both reliability studies had small sample size. The effect of the small sample size in the reliability study was discussed in detail in section 3.4 in chapter 3. To reiterate, the results of the reliability studies were acceptable despite the small sample size as the results were viewed as descriptive statistics that do not provide definitive information. Both reliability studies were considered as pilot studies and their results were only used for the purposes of the larger main research presented in this thesis. It should be born in mind that the impact of the small sample size in the main experimental study is different than the reliability study. While the statistical significance is of concern in the main experimental study with a small sample size, the magnitude of the reliability estimates need to be addressed in a reliability study with a small sample (Morrow and Jackson, 1993).

Another limitation in the balance test was the length of time determined for the test, which was 10 seconds. Results of this study showed that there was no statistical difference between the two groups, however, a noticeable difference was observed by the researcher during the data collection as patients tend to struggle to maintain their balance while healthy participants managed to stand more stable and for longer than 10 seconds. The length of the test should have not been determined as 10 seconds and participants should have been asked to stand on one leg as long as they can. This would make the study more clinically relevant as this is commonly done by clinicians in practice. It is also expected that longer test might reveal the differences between the two groups that were observed by the researcher but not big enough to be statistically significant.

This study only investigated the sensorimotor function in patients with chronic tennis elbow, pain testing was not included. However, all the theories underpinning central sensitisation link sensorimotor deficits to the persistence of pain. Therefore, future research investigating sensorimotor deficits should involve pain investigation as well. It is also recommended to include some qualitative aspect of pain perception in these patients in order to understand the mechanism of central sensitisation hypothesised in chronic tennis elbow.

5.6 Implications of this work and future research

This research was a novel study into general sensorimotor deficits in patients with tennis elbow. Therefore, definitive findings could not be drawn from this research, nor recommendation concerning the diagnosis and treatment of tennis elbow as they need to be supported by further research. However, clinicians involved in the management of tennis elbow are encouraged to challenge their own classical beliefs about the condition and acknowledge its multifactorial pathology. Especially those old theories about tennis elbow in regard to its pathology were not proved true. Further studies are warranted to reach definitive conclusions taking the following issues into consideration.

As discussed earlier, a number of theories have been proposed in an attempt to explain the bilateral sensorimotor deficits in chronic tennis elbow. Although these

theories might look different, they all relate the sensorimotor deficits to the persistence of pain. The latter may trigger the process of central sensitisation and cortical reorganisation; consequently this will serve an important function in the persistence of pain. This suggests that sensorimotor function and pain are linked together in a cyclical way that reinforces the pain perceived by the patient. Therefore, any attempt to understand the sensorimotor function in chronic tennis elbow would not be complete without addressing the pain in these patients. However, the literature shows that sensorimotor function and pain have been studied separately in patients with chronic tennis elbow. Future research should look into the sensorimotor deficits along with pain in these patients.

Postural control was investigated during single leg standing with eyes are closed and open. Single leg standing is a common balance test performed by clinicians to identify any possible postural control deficit. Whilst this makes the findings of this study clinically relevant it does not necessarily represent a daily life activity. Therefore, future research could address this issue by investigating postural control while performing activities that involve recovering and stepping strategies as they resemble a situation where the individual's balance might be threatened in a real life scenario.

Beside the issues already identified, further research should include larger sample size. The next section discusses the issue of sample size calculation and estimated sample sizes that are required to reach statistical significance were calculated based on the results of this research.

5.6.1 Sample size calculation

The results of this study did not reach statistical significance and had relatively low sample size for reasons mentioned earlier. However, this is acceptable given that this study was an exploratory study that aims to generate hypothesis. Nevertheless, further research is needed in order to provide definitive answers; therefore, the sample size needs to be larger than this study. Sample size calculation is the process that estimates number of participants that is required to yield a specified clinically relevant effect size. Sample size calculation is important in the design phase of the research and while interpreting the findings as well.

For the purposes of future research, the number of participants that should be recruited in order to achieve the desired statistical power was calculated. There are different ways to calculate the sample size, some could be calculated manually using specific equations while others involve using special software such as G power, which is free to download. The sample size presented in Table 32 was calculated using the following equation adopted from Torgerson and Miles (2007):

$$\mathbf{N} = \frac{32}{d^2} \qquad \textbf{(Equation 5.1)}$$

Where N is the sample size and d is the square root of the standardised effect which was calculated by dividing the difference in the means between the two groups by the standard deviation of the healthy participants.

This equation is easy to remember and calculate, therefore, it encourages clinicians to engage in the good practice of calculating the sample size during their research design to avoid underpowered studies. It is noteworthy to mention that scientific journals are increasingly demand sample size calculations. Based on the results of this research and using equation 5.1, the sample sizes were calculated for each outcome measure used in this research, see Table 32.

Outcome measure	Total sample size	Each group
TtB ap	52	26
TtB ml	1562	781
1-choice RT	3249	1624
2-choice RT	670	335

Table 32: Estimated sample sizes.

The sample sizes presented in Table 32 are relatively very large apart from the TtB ap which is the only measure that approached significance in this study and had a medium size effect. It should be born in mind that too large sample size could be wasteful of resources and ethically questioned as it might expose participants to unnecessary risk (Columb and Stevens 2008). Most importantly in this case, very large sample size is very difficult to obtain, especially that tennis elbow affects 1 in every 1000 people and we are interested only in chronic patients. Therefore, it might be useful

to look at another way to estimate the sample size, based on Cohen (1992), the following guideline could be used: if the α level was set at 0.05 and require the recommended power of 0.8, then 783 participants are needed to detect a small effect size ($r = 0.1$), 85 participants are needed to detect a medium effect size ($r = 0.3$) and 28 participants is needed to detect a large effect size ($r = 0.5$). This might be a crude estimate of sample size, however, it could be used as guideline in situations where there is no similar studies to compare with as it gives an idea about the expected number of participants.

Furthermore, the sample sizes presented in Table 32 were calculated based on the results obtained in this study, therefore, it should be born in mind the limitations of the protocol and equipment used to measure the response time in this study. Further research should address these limitations as they might have contributed to the insignificant results of this study.

5.7 Conclusion

Following an extensive literature review it became apparent that there was a lack of research evidence investigating the generalised sensorimotor function in patients with chronic tennis elbow. This was the first study to investigate balance and response time of the lower limb in patients with chronic tennis elbow. The overall aim of the study was to investigate the generalised sensorimotor function in these patients. Findings from this innovative study have shown that patients with chronic tennis elbow were closer to reach their stability boundary in the ap direction when compared to healthy participants. This suggests that these patients have more balance instability than healthy participants. The new knowledge provided by this work enhances our understanding of the sensorimotor function in patients with chronic tennis elbow and opens new avenues of research in this field. This work demonstrates the link between scientific research and clinical practice as this study was originally inspired by clinical observation made by experts in tennis elbow management. The findings need to be translated into clinical practice enabling physiotherapists to keep updated with new research findings in order to provide evidence based practice to their patients. Bearing in mind that sensorimotor deficits are not currently integrated in the management of tennis elbow, the findings of

this research helps to bridge the gap between science and current practice by enhancing the understanding of the condition.

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Appendices

Appendix 1: Forms

a. Screening form (Healthy participants)
b. Consent form (Healthy participants)
c. Participants information sheet (Healthy participants)
d. Poster (Healthy participants)
e. Screening form (Patients with tennis elbow)
f. Consent form (Patients with tennis elbow)
g. Participants information sheet (Patients with tennis elbow/ Northern General Hospital)
h. Participants information sheet (Patients with tennis elbow/ Primary Care Trust)

SCREENING FORM

Balance and postural control in healthy males and females

- **This form contains some questions, the information you give is important.**
- **If your age is in the range between 35-65 please answer the following questions.**

Please remember that:

- **Confidentiality is ensured as no one will access the data except the researcher.**
  - Name:
  - Date of birth:
  - Sex: Male / Female
  - Dominancy of Hand (which one you use for writing): Right / Left
  - Dominancy of foot (which one you use to kick a ball): Right / Left
  - Acuity of vision: Normal / corrected to normal / not corrected visual problems

Please ring as appropriate, do you have:

- Lower extremity (leg or foot) musculoskeletal injury in the previous six months
  YES / NO
- Pain at your elbow and / or outer side of your arm (Tennis elbow)
  YES / NO
- Back injury or back pain in the previous six months
  YES / NO
- Head related injury in the previous six months (e.g.cerebral concussions)
  YES / NO
- Vestibular disorders (dizziness)
  YES / NO
- Neurological conditions (e.g. Stroke, Parkinson, ataxia, MS)
  YES / NO
- Do you take any medication that affects your balance
  YES / NO
- If you are a female, do you have:
  MENSTRUAL CYCLES / MENOPAUSE

Thanks for your time ☺

Your participation is appreciated

* If you have any question please feel free to contact

Researher's name and contact details were provided here.

PARTICIPANT INFORMATION SHEET
(THE BALANCE AND RESPONSE TIME IN HEALTHY MIDDLE AGED MALES AND FEMALES)

You are invited to participate in a study to test your balance and response time.

"Why I have been asked to take part in this study?"

We have designed a study to test the balance and reaction time of men and women between the ages of 35 and 65 as the first part of a bigger study to establish whether a link exists been poor balance and the development of a painful elbow, called tennis elbow in people of your age. This condition can occur in the absence of playing tennis and as a result of working at home or in the office. The bigger study will repeat this research but with people who have tennis elbow. We hope to ultimately develop physiotherapy programme to prevent and treat tennis elbow.

"How long will the study last?"

You will be involved for an hour.

"What will it involve?"

If you agree to participate in this study you will be asked to fill a screening form. If you are eligible to join the study then you will be invited o measure your balance and reaction time.

"What is the procedure, and are there side-effects?"

Balance test: You will be asked to stand on one leg on a balance measuring device (rectangular piece) placed on the floor, you will stand on your right leg then your left leg with your eyes closed and eyes opened. Each test will be done three times.

Reaction time test: Your arms and legs response time will be tested from sitting. The measuring device will be a portable board that contains five pads (one in the centre and four placed in a crescent shape and will have lights underneath). You need to put your hand/ foot on the central pad and release it when you see the light.

"Where the study will be done?"

The study will be carried out in Sheffield Hallam University / Collegiate Hall.

"How often will I have to come?"

Once.

"What If I don't wish to take part?"

It is completely up to you. There is no problem if you decide not to take part in the study.

"What if I change my mind during the study?"

You are free to withdraw from the study at any time.

"What will happen to the information from the study?"

All information will be kept entirely confidential. No individual will be identifiable in the report. You will be informed of the results of the study if you wish

"What if I have further questions?"

If you have any questions, please contact:

Researher's name and contact details were provided here.

CONSENT FORM

Balance and response time in healthy males and females.

Please give your consent to participating in the study by answering the following questions (please tick the boxes)

Have you read the information sheet about t his study? Yes☐ No☐
Have you been able to ask questions about this study? Yes☐ No☐
Have you received answers to all your questions? Yes☐ No☐
Have you received enough information about this study? Yes☐ No☐

Which investigator have you spoken to about this study? .....

Are you involved in any other studies? Yes☐ No☐

- If you are, how many?

Do you understand that you are free to withdraw from this study?

- At any time? Yes☐ No☐
- Without giving a reason for withdrawing? Yes☐ No☐

Do you agree to take part in this study? Yes☐ No☐

Your signature will clarify that you have had adequate opportunity to discuss the study with the investigator and have voluntarily decided to take part in this study.

Please keep your copy of this form and the information sheet together.

Signature of participant.....Date.....

Name (Block letters):.....

Signature of investigator:.....

Do you have Tennis Elbow?

Are you aged between 35 and 65 years?

You are invited to join a study on tennis elbow. This study is part of a PhD programme; findings could help health professionals to better understand tennis elbow and provide better assessment and treatment for patients.

The study will include balance and response time tests, so should be enjoyable! It will last about an hour.

If you are interested or if you have any queries, please do not hesitate to contact me:

Researher's name and contact details were provided here.

SCREENING FORM

Balance and postural control in people with tennis elbow

- **This form contains some questions, the information you give is important.**
- **If your age is in the range between 35-65 please answer the following questions.**

Please remember that:

- **Confidentiality is ensured as no one will access the data except the researcher.**
  - Name:
  - Date of birth:
  - Sex: Male / Female
  - Dominancy of Hand (which one you use for writing): Right / Left
  - Dominancy of foot (which one you use to kick a ball): Right / Left
  - Acuity of vision: Normal / corrected to normal / not corrected visual problems.

Please ring as appropriate, do you have:

- Lower extremity (leg or foot) musculoskeletal injury in the previous six months
  YES / NO
- Pain at your elbow and / or outer side of your arm (Tennis elbow)
  YES / NO
- Back injury or back pain in the previous six months
  YES / NO
- Head related injury in the previous six months (e.g.cerebral concussions)
  YES / NO
- Vestibular disorders (dizziness)
  YES / NO
- Neurological conditions (e.g. Stroke, Parkinson, ataxia, MS)
  YES / NO
- Do you take any medication that affects your balance
  YES / NO
- If you are a female, do you have:
  MENSTRUAL CYCLES / MENOPAUSE

Thanks for your time ☺

Your participation is appreciated

* If you have any question please feel free to contact

Researher's name and contact details were provided here.

CONSENT FORM

Balance and postural control in people with tennis elbow.

Please give your consent to participating in the study by answering the following questions (please tick the boxes)

Have you read the information sheet about this study?	Yes☐	No☐
Have you been able to ask questions about this study?	Yes☐	No☐
Have you received answers to all your questions?	Yes☐	No☐
Have you received enough information about this study?	Yes☐	No☐

Are you involved in any other studies? Yes☐ No☐

- If you are, how many?

Do you understand that you are free to withdraw from this study?

- At any time? Yes☐ No☐
- Without giving a reason for withdrawing? Yes☐ No☐

I understand that relevant sections of my medical notes and data collected during the study may be looked at by individuals from regulatory authorities or from the NHS Trust, where it is relevant to my taking part in this research. I give permission for these individuals to have access to my records.

Yes☐ No☐

I understand that the information will be kept on paper and computer database and that access will be restricted to the researchers. Yes☐ No☐

I agree to take part in this study? Yes☐ No☐

Your signature will clarify that you have had adequate opportunity to discuss the study with the researcher and have voluntarily decided to take part in this study.

Please keep your copy of this form and the information sheet together.

Name of participant	Date	Signature
.....	.....	.....
Name of researcher	Date	Signature
.....	.....	.....

PARTICIPANT INFORMATION SHEET

(The Balance and response time in people diagnosed with tennis elbow)

You are invited to participate in a research study to test your balance and response time. Your balance will be tested when standing on one leg with your eyes opened and closed. Before you decide to take part in the study please take time to read the following information. If you have any questions or you want more information do not hesitate to contact me on the address provided at the end of this information sheet.

Thank you for reading this.

"What is the title of the study?"

The balance and postural control in middle aged people diagnosed with tennis elbow.

"What is the purpose of the study?"

As part of my PhD, I have designed a study to test the balance of men and women diagnosed with tennis elbow or shoulder problems between the ages of 40 and 59 to establish whether a link exists between poor balance and the development of tennis elbow. We hope that the results of this study will help us to ultimately develop physiotherapy exercises that treat these problems effectively in the future.

Some people with tennis elbow continue to have pain even after the different methods of treatment and some suffer from poor balance that is not being treated, we want to explore if there is a link between poor balance and tennis elbow.

"Why I have been asked to take part in this study?"

You have been invited to participate in the study because you were diagnosed with tennis elbow or shoulder problem.

"Do I have to take part?"

It is up to you whether or not to take part. If you decide to take part you will be given this information sheet to keep and you will be asked to sign a consent form. If you decide to take part you are still free to withdraw from the study at any time and without giving any reason. If you decide not to take part in the study or if you withdraw later, this will not affect the standard of care you receive from any health or social care service.

"What will happen if I want to take part?"

You will be given a consent form to sign and the test will be explained again in detail.

"How long will the study last?"

The whole study will last about two months. You will be involved for about an hour.

"What will it involve?"

If you agree to participate in this study you will be asked to fill a health questionnaire. If you are eligible to join the study then I will measure your balance as you stand on one leg and test how quick and accurate your response is to a light.

"What is the procedure, and are there side-effects?"

Balance test: You will be asked to stand on one leg on a balance measuring device (rectangular piece) placed on the floor, you will stand on your right leg then your left leg with your eyes closed and eyes opened. Each test will be done three times.

Response time test: the test will be done using a board with pads on it, you will place your hand or foot in the middle and you will be asked to move your hand or foot when you see the light from one of the pads.

"Where the study will be done?"

The study will be carried out in Northern General Hospital / Orthopedic Clinic.

"How often will I have to come?"

Only this time.

"Will taking part cost me?"

No, you will be paid the parking fees and will be offered refreshment.

"What If I don't wish to take part?"

It is completely up to you. There is no problem if you decide not to take part in the study and this will not affect the standard of care you receive form any health or social care services.

"What if I change my mind during the study?"

You are free to withdraw from the study at any time without giving any reason.

"What will happen to the information from the study?"

All information will be kept entirely confidential. No individual will be identifiable in the report. You will be informed of the results of the study if you wish.

"Will my taking part in the study be kept confidential?"

Yes, all the information collected about you during the study will be kept strictly confidential. You will be identified by a code number rather a name, your name will not be disclosed.

"What if there is a problem?"

Any complaint about the way you have been dealt with during the study or any possible harm you might suffer will be addressed. If you are harmed by taking part in the study, there are no special compensation arrangements. If you wish to complain, or have any concerns about any aspect of the way you have been approached during this study, the normal National Health Service Complaints mechanisms should be available to you. You can contact Mr. Dave Stanley for details or if you have internet access you can make a complaint directly using the following links:

http://www.direct.gov.uk/en/Diol1/DoItOnline/DG_4018299

http://www.nhs.uk/servicedirectories/pages/hospital.aspx?id=rhqnq&v=4

"Who has reviewed this study?"

All research in the NHS is looked at by an independent group of people, called a Research Ethics Committee to protect your interests. This study has been reviewed and given favorable opinion by South Yorkshire Ethics Committee.

"Further information/independent advice"

Patient Advice and Liaison Service

Sheffield PCT

Firth Park Clinic/ North Quadrant

Sheffield S5 6NU

Tel: 0114 2262360

"What if I have further questions?"

If you have any questions now or later, please contact me at the address below:

Researcher's name and contact details were provided here

Version: 2 Date: 19/10/2009

PARTICIPANT INFORMATION SHEET

(The Balance and response time in people diagnosed with tennis elbow)

You are invited to participate in a research study to test your balance when standing on one leg with your eyes opened and closed. Before you decide to take part in the study please take time to read the following information. If you have any questions or you want more information do not hesitate to contact me on the address provided at the end of this information sheet.
Thank you for reading this.

"What is the title of the study?"

The balance and postural control in middle aged people diagnosed with tennis elbow and shoulder problems.

"What is the purpose of the study?"

As part of my PhD, I have designed a study to test the balance of men and women diagnosed with tennis elbow or shoulder problems between the ages of 40 and 59 to establish whether a link exists between poor balance and the development of tennis elbow or shoulder problems. We hope that the results of this study will help us to ultimately develop physiotherapy exercises that treat these problems effectively in the future.
Some people with tennis elbow continue to have pain even after the different methods of treatment and some suffer from poor balance that is not being treated, we want to explore if there is a link between poor balance and tennis elbow or shoulder problems.

"Why I have been asked to take part in this study?"

You have been invited to participate in the study because you were diagnosed with tennis elbow or shoulder problem.

"Do I have to take part?"

It is up to you whether or not to take part. If you decide to take part you will be given this information sheet to keep and you will be asked to sign a consent form. If you decide to take part you are still free to withdraw from the study at any time and without giving any reason. If you decide not to take part in the study or if you withdraw later, this will not affect the standard of care you receive from any health or social care service.

"What will happen if I want to take part?"

You will be given a consent form to sign and the test will be explained again in detail.

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The whole study will last about two months. You will be involved for about an hour.

"What will it involve?"

If you agree to participate in this study you will be asked to fill a health questionnaire. If you are eligible to join the study then I will measure your balance as you stand on one leg and test how quick and accurate your response is to a light.

"What is the procedure, and are there side-effects?"

Balance test: You will be asked to stand on one leg on a balance measuring device (rectangular piece) placed on the floor, you will stand on your right leg then your left leg with your eyes closed and eyes opened. Each test will be done three times.

Response time test: the test will be done using a board with pads on it, you will place your hand or foot in the middle and you will be asked to move your hand or foot when you see the light from one of the pads.

"Where the study will be done?"

The study will be carried out in a GP surgery close to your home.

"How often will I have to come?"

Only this time.

"Will taking part cost me?"

No, you will be paid the parking fees and will be offered refreshment.

"What If I don't wish to take part?"

It is completely up to you. There is no problem if you decide not to take part in the study and this will not affect the standard of care you receive form any health or social care services.

"What if I change my mind during the study?"

You are free to withdraw from the study at any time without giving any reason.

"What will happen to the information from the study?"

All information will be kept entirely confidential. No individual will be identifiable in the report. You will be informed of the results of the study if you wish.

"Will my taking part in the study be kept confidential?"

Yes, all the information collected about you during the study will be kept strictly confidential. You will be identified by a code number rather a name, your name will not be disclosed.

"What if there is a problem?"

Any complaint about the way you have been dealt with during the study or any possible harm you might suffer will be addressed. If you are harmed by taking part in the study, there are no special compensation arrangements. If you wish to complain, or have any concerns about any aspect of the way you have been approached during this study, the normal National Health Service Complaints mechanisms should be available to you. If you have internet access you can make a complaint directly using the following links:

http://www.direct.gov.uk/en/Dio11/DoItOnline/DG_4018299

http://www.nhs.uk/servicedirectories/pages/hospital.aspx?id=rhqnq&v=4

"Who has reviewed this study?"

All research in the NHS is looked at by an independent group of people, called a Research Ethics Committee to protect your interests. This study has been reviewed and given favorable opinion by South Yorkshire Ethics Committee.

"Further information/independent advice"

Patient Advice and Liaison Service

Sheffield PCT

Firth Park Clinic/ North Quadrant

Sheffield S5 6NU

Tel: 0114 2262360

"What if I have further questions?"

If you have any questions now or later, please contact me at the address below:

Researher's name and contact details were provided here.

Appendix 2: Data Analysis and results

This appendix includes the SPSS modified output of box plots, histograms, Q-Q plots, results of Levene's test of homogeneity of variance, results of Kolmogorov-Smirnov test of normality and results of mixed ANOVA. Significant values of normality test, homogeneity of variance test and mixed ANOVA are highlighted in grey inside tables.

1 Balance Data- Time to Boundary ap and ml

1.1 Descriptive statistics

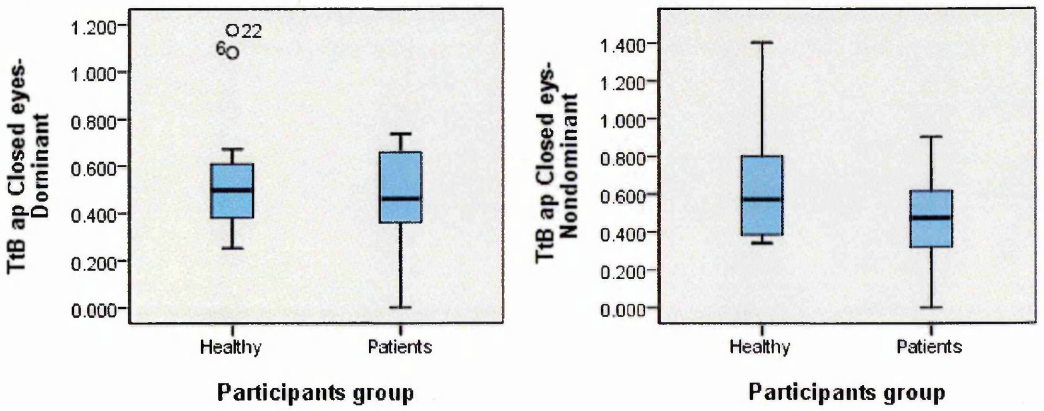
Descriptive statistics		Healthy participants				Patients with tennis elbow			
		Closed eyes/ Dominant LL	Closed eyes/ Non dominant LL	Opened eyes/ Dominant LL	Opened eyes/ Non dominant LL	Closed eyes/ Ipsi-lateral LL	Closed eyes/ Contra-lateral LL	Opened eyes/ Ipsi-lateral LL	Opened eyes/ Contra-lateral LL
Std. Error of Mean		0.048	0.059	.136	0.142	0.078	0.074	0.175	0.135
Median		0.497	0.571	1.701	1.794	0.460	0.472	1.367	1.691
Mode		0.251	0.342	0.929	1.169	0.000	0.000	0.559	0.600
Variance		0.051	0.077	0.410	0.442	0.067	0.059	0.336	0.200
Minimum		0.251	0.342	0.929	1.169	0.000	0.000	0.559	0.600
Maximum		1.178	1.403	3.273	3.789	0.736	0.903	2.559	2.139
Percentiles	25	0.373	0.384	1.388	1.479	0.309	0.278	0.939	1.626
	50	0.497	0.571	1.701	1.794	0.460	0.472	1.367	1.691
	75	0.610	0.805	2.097	2.302	0.679	0.619	1.785	1.796

Table 1: Descriptive statistics for TtB ap.

Descriptive statistics		Healthy participants				Patients with tennis elbow			
		Closed eyes/ Dominant LL	Closed eyes/ Non dominant LL	Opened eyes/ Dominant LL	Opened eyes/ Non dominant LL	Closed eyes/ Ipsi-lateral LL	Closed eyes/ Contra-lateral LL	Opened eyes/ Ipsi-lateral LL	Opened eyes/ Contra-lateral LL
Std. Error of Mean		0.015	0.016	0.041	0.042	0.028	0.028	0.035	0.076
Median		0.170	0.158	0.431	0.442	0.179	0.206	0.421	0.527
Mode		0.108	0.102	0.289	0.250	0.000	0.000	0.226	0.233
Variance		0.005	0.006	0.037	0.038	0.009	0.008	0.014	0.064
Minimum		0.108	0.102	0.289	0.250	0.000	0.000	0.226	0.233
Maximum		0.406	0.403	0.958	0.953	0.286	0.370	0.710	1.166
Percentiles	25	0.139	0.132	0.394	0.373	0.133	0.118	0.375	0.376
	50	0.170	0.158	0.431	0.442	0.178	0.206	0.421	0.527
	75	0.209	0.211	0.660	0.573	0.232	0.215	0.491	0.607

Table 2: Descriptive statistics for TtB ml.

1.2 Outliers in the time to boundary data



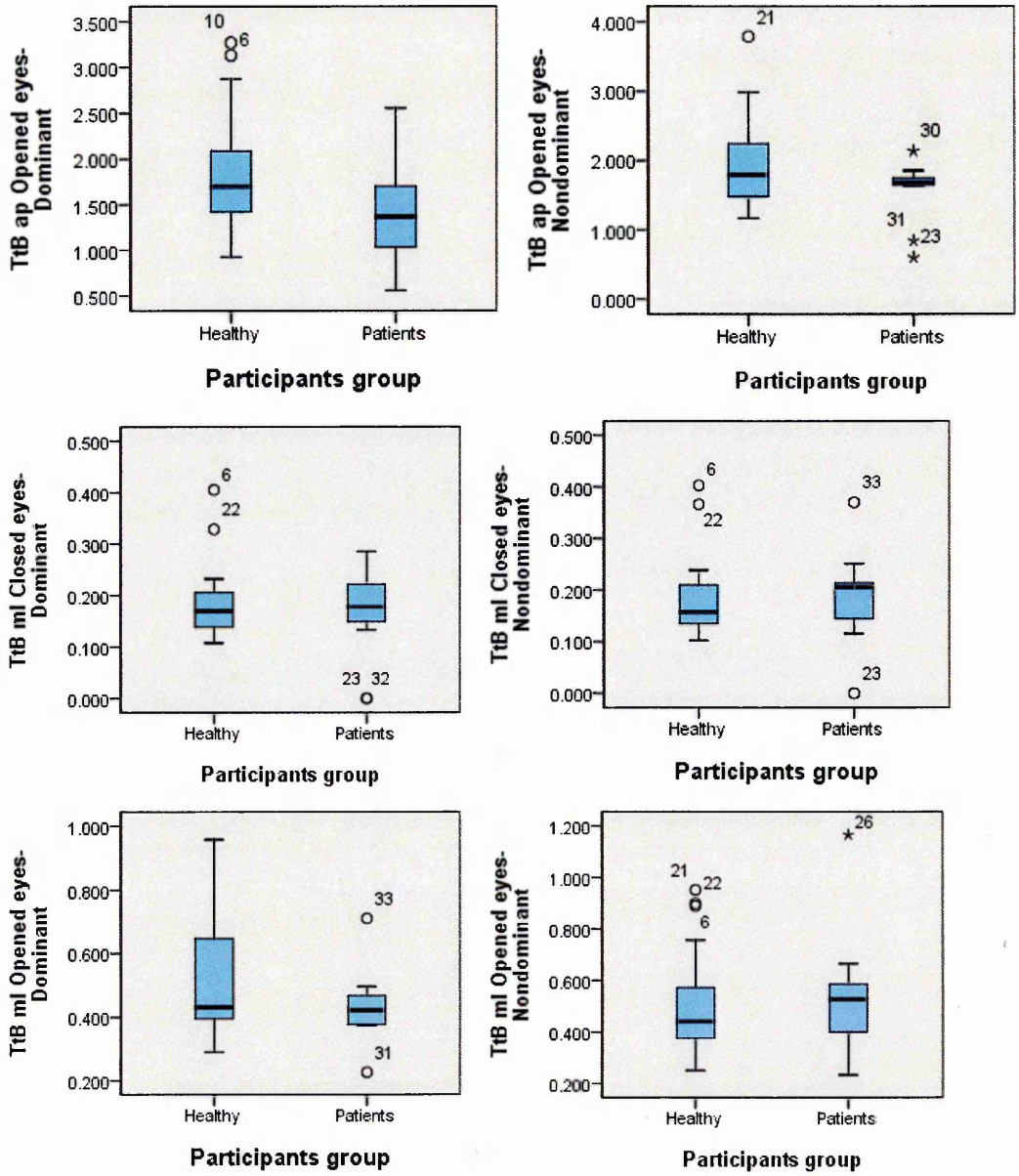


Figure 1: Box plots of TtB ap and ml data for healthy participants and patients with tennis elbow.

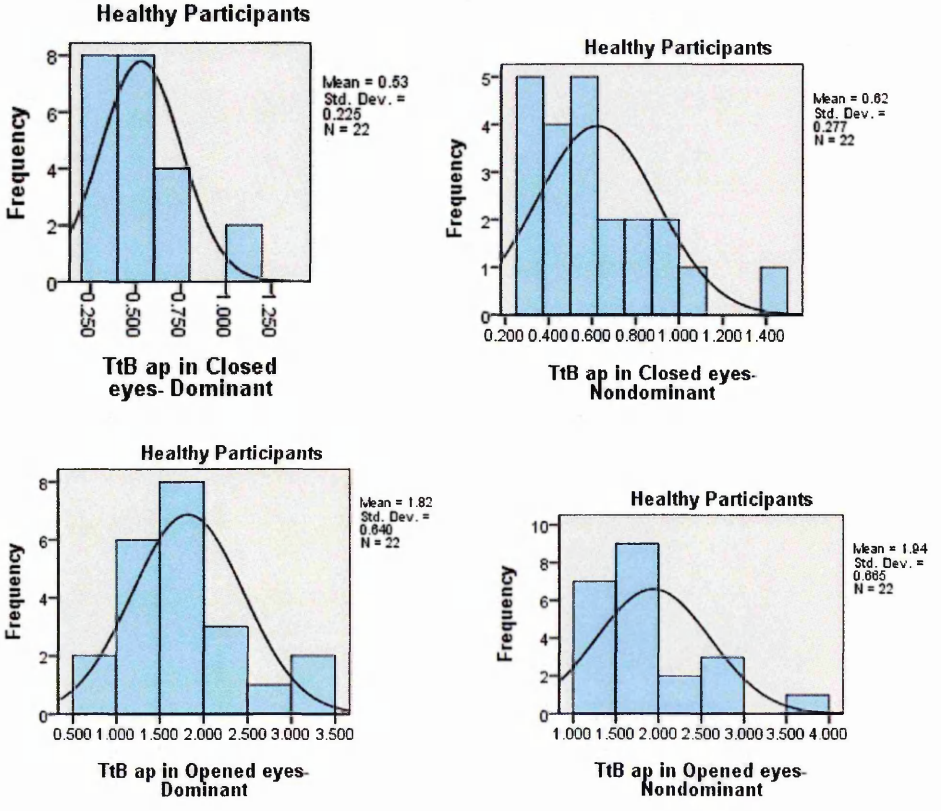
1.3 Checking the assumptions for TtB data

1.3.1 Normality

To check the assumption of normality, TtB data were visually inspected using histograms and Q-Q plots then values of skew and kurtosis were checked and their z scores were calculated. Finally, the distribution of the data was tested using Kolmogorov-Smirnov test.

1.3.1.1 Histograms and Q-Q plots

The TtB data were plotted using Q-Q plots and histograms (Figure 1-4). The Q-Q stands for the quantile-quantile plot which is a graph that plots the quantiles of a variable against the quantiles of other distribution; in this case the normal distribution is the distribution of interest (Field 2009). If the values of the studied variable fall on the diagonal of the plot then this variable has the same distribution as the normal distribution. While if there are deviations from the diagonal then this means deviations from the normal distribution. The histograms were visually checked for skeweness and kurtosis, in healthy participants the TtB ap scores were positively skewed in the closed eyes-dominant, closed eyes-non dominant and opened eyes-non dominant (Figure 1), TtB ml scores were also positively skewed in healthy participants in the closed eyes-dominant and closed eyes-non dominant (Figure 3). In the patients group, TtB ap was positively skewed in the opened eyes-dominant variable (Figure 1) and the TtB ml was also positively skewed in the opened eyes-non dominant variable (Figure 3). The skeweness observed in the histograms is also seen in the Q-Q plots as deviations from the diagonal line towards an S-shaped curve (Figure 2 and 4).



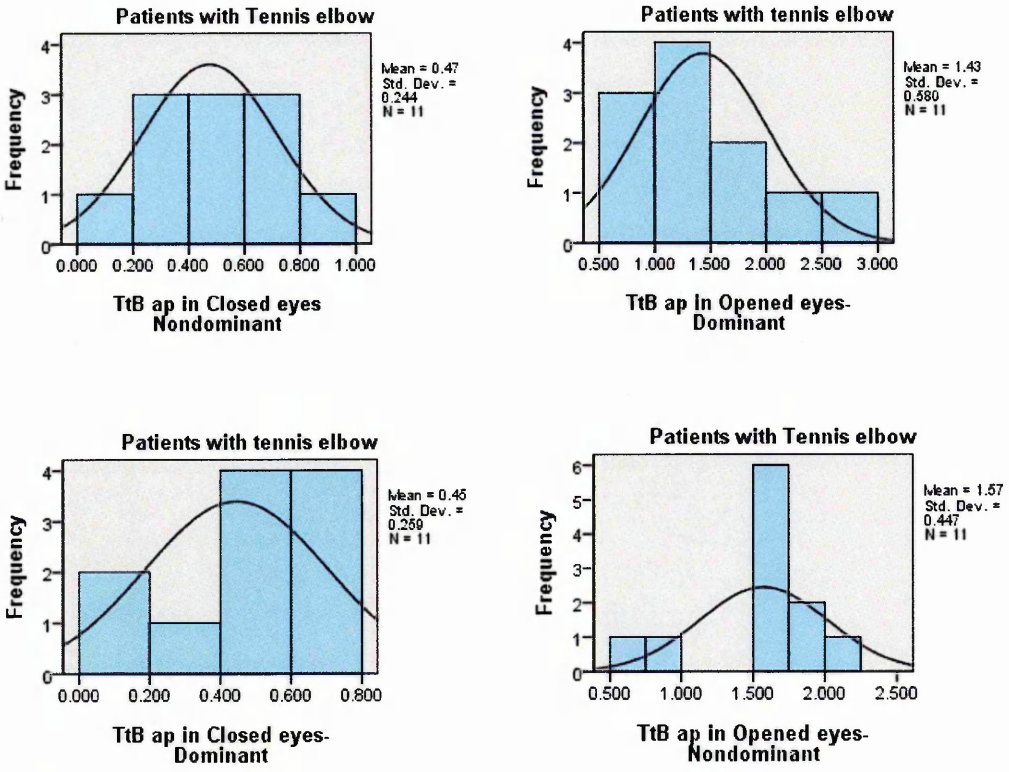
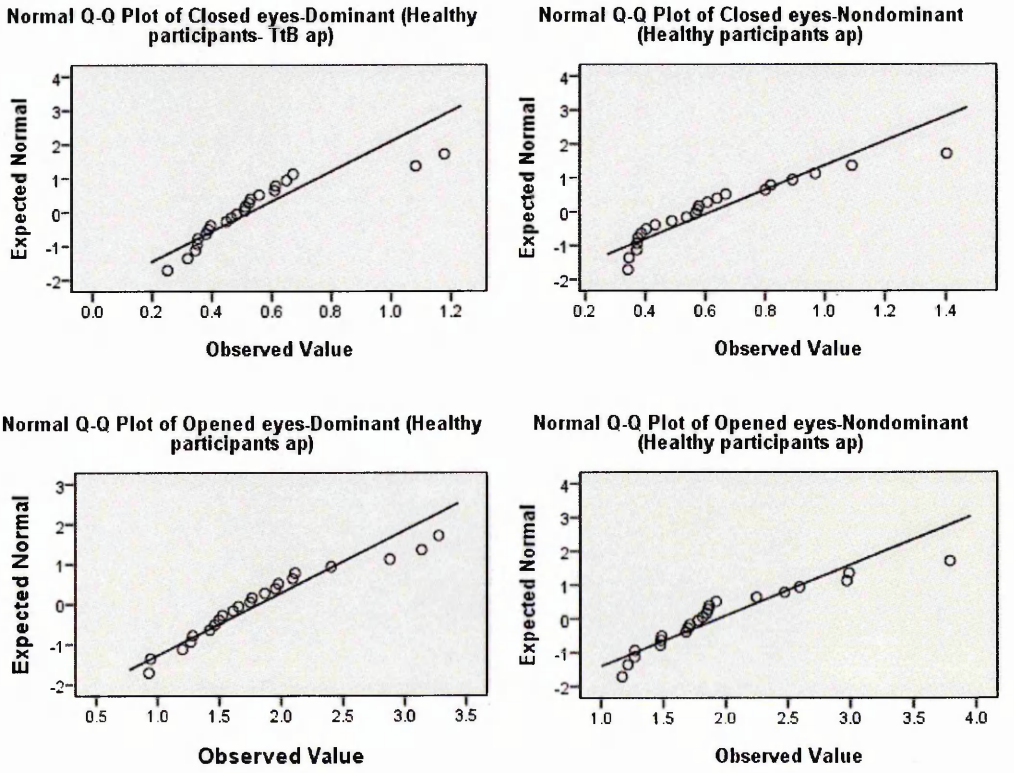


Figure 2: Histograms of TtB ap.



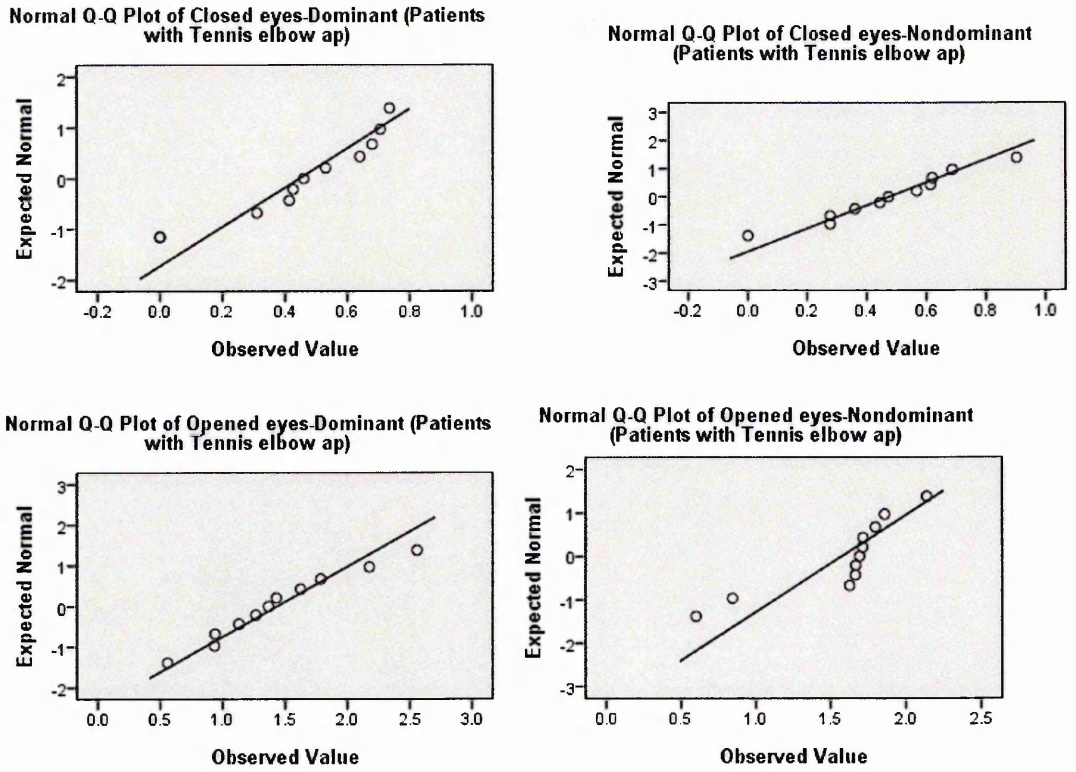
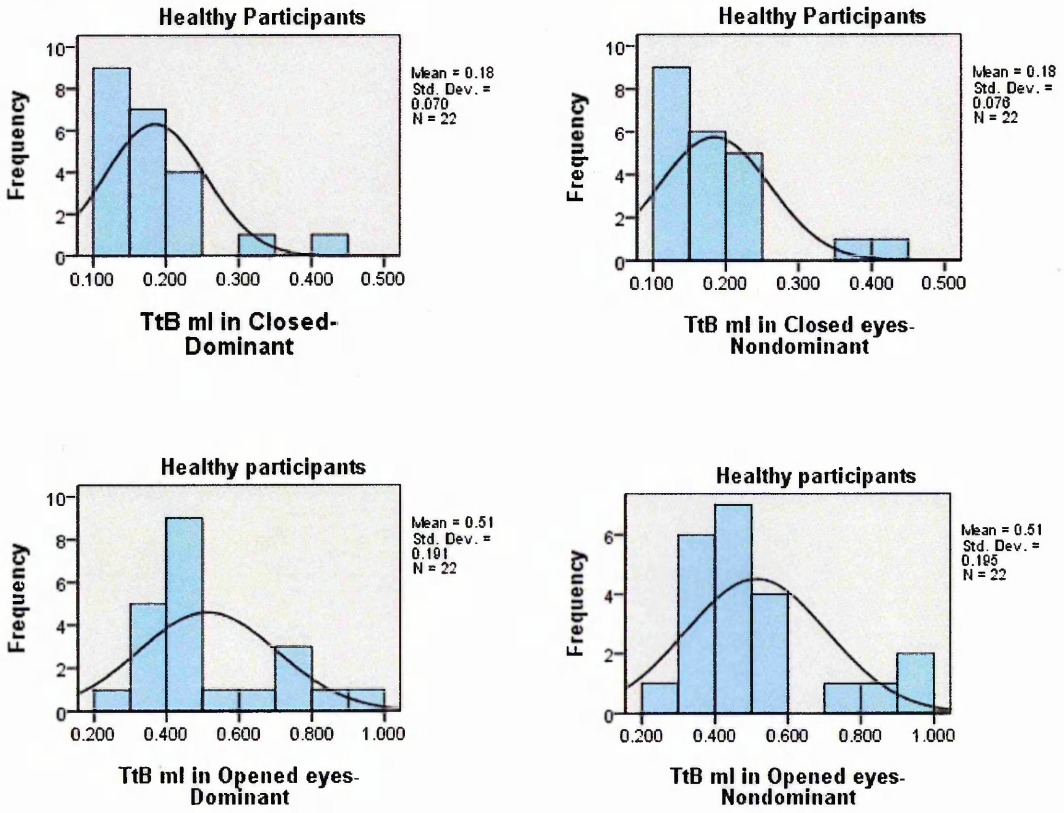


Figure 3: Q-Q plots of TtB ap.



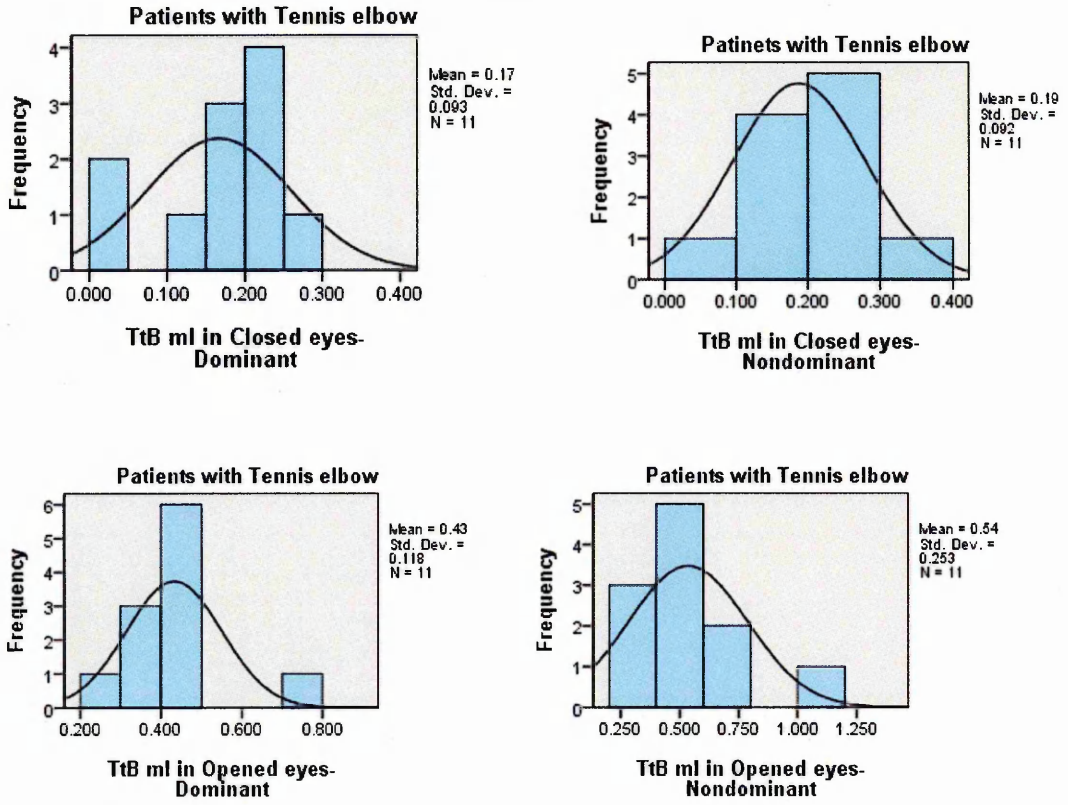
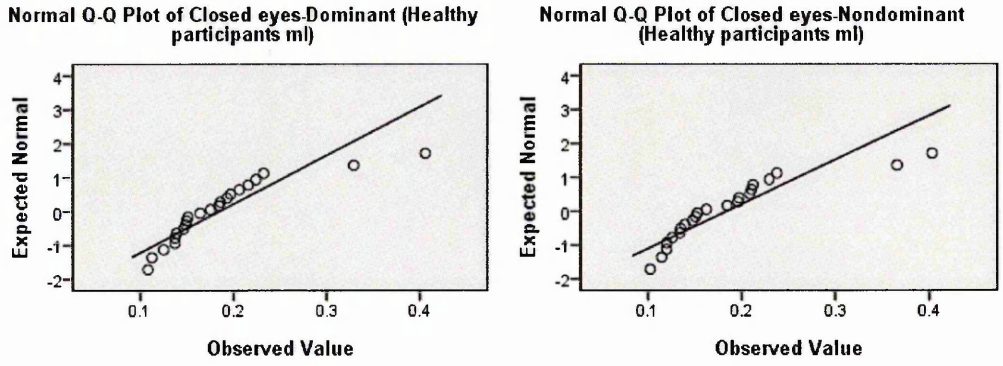


Figure 4: Histograms of TtB ml.



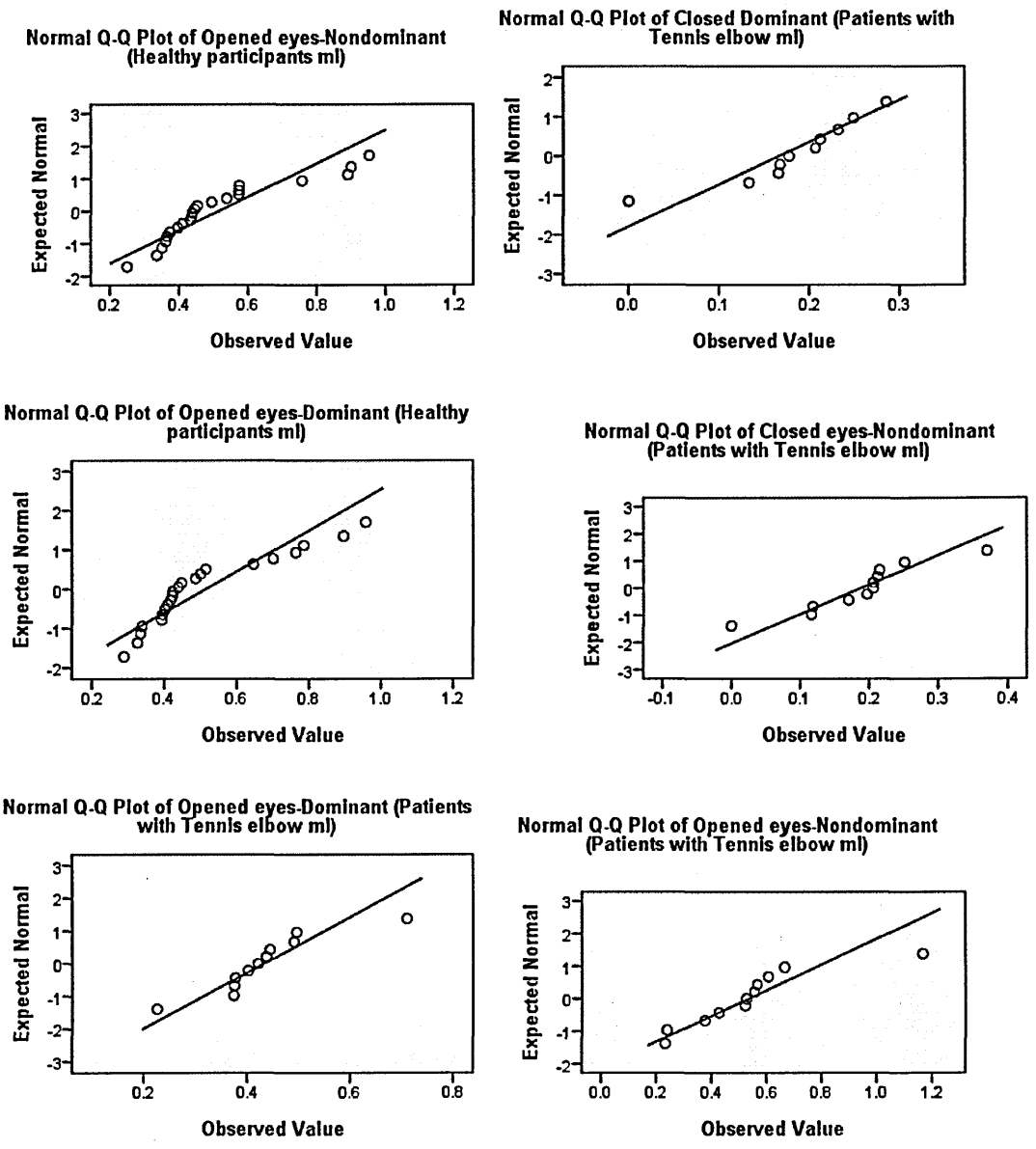


Figure 5: Q-Q plots of TtB ml.

1.3.1.2 Skewness and Kurtosis scores and their z-scores

Skeweness and kurtosis scores were converted to *z*-scores by dividing by their corresponding standard error, these *z*-scores were compared against known values for the normal distribution that are expected to occur by chance alone, therefore, values of *z*-scores greater than 1.96 are significant at $p<0.05$ (Table 3-6).

Healthy Participants				
	CD	CN	OD	ON
Skewness	1.799	1.322	.939	1.312
Std. Error of Skewness	.491	.491	.491	.491
z skewness[1]	3.664	2.692	1.912	2.672
Kurtosis	3.521	1.652	.477	1.582
Std. Error of Kurtosis	.953	.953	.953	.953
z kurtosis[2]	3.695	1.733	.501	1.66

Table 3: Skewness and Kurtosis scores for TtB ap.

Patients with Tennis elbow				
	CD	CN	OD	ON
Skewness	-.822	-.245	.589	-1.485
Std. Error of Skewness	.661	.661	.661	.661
z skewness	-1.243	-.371	.891	-2.247
Kurtosis	-.262	.526	.120	1.752
Std. Error of Kurtosis	1.279	1.279	1.279	1.279
z kurtosis	-.205	.411	.094	1.37

Table 4: Skewness and Kurtosis scores for TtB ap.

Healthy Participants				
	CD	CN	OD	ON
Skewness	1.922	1.733	1.132	1.192
Std. Error of Skewness	.491	.491	.491	.491
z skewness	3.914	3.53	2.305	2.428
Kurtosis	4.354	3.112	.217	.542
Std. Error of Kurtosis	.953	.953	.953	.953
z kurtosis	4.569	3.265	.228	.569

Table 5: Skewness and Kurtosis scores for TtB ml.

Patients with Tennis elbow				
	CD	CN	OD	ON
Skewness	-1.009	-.139	.945	1.481
Std. Error of Skewness	.661	.661	.661	.661
z skewness	-1.526	-2.103	1.43	2.241
Kurtosis	.346	1.972	3.352	3.751
Std. Error of Kurtosis	1.279	1.279	1.279	1.279
z kurtosis	.271	1.542	2.621	2.933

Table 6: Skewness and Kurtosis scores for TtB ml.

[1] $Z_{skewness} = \frac{skewness - 0}{Std.Error_{Skewness}}$

[2] $Z_{kurtosis} = \frac{Kurtosis - 0}{Std.Error_{Kurtosis}}$

After ignoring the minus sign, values of z-scores greater than 1.96 are significant at $p<.05$. z-scores that are significantly skewed or kurtosis are highlighted in grey (Table 3-6).

1.3.1.3 The Kolmogorov-Smirnov test

The Kolmogorov-Smirnov (K-S) test was conducted to see if the TtB scores distribution significantly differs from a normal distribution. The K-S test was significant for four variables of the TtB data, TtB ap in the opened eyes-non dominant in patients with tennis elbow and healthy participants (Table 7) and TtB ml in the opened and closed-non dominant in healthy participants (Table 8). From the visual observation of histograms, checking z-scores and mainly the results of K-S test we infer that TtB data were non-normally distributed in the variables mentioned earlier.

The TtB ap scores in ON, $D(22) = 0.236$, $p < 0.05$ and TtB ap scores in ON, $D(11) = 0.365$, $p < 0.001$, were both significantly non-normal. For the TtB ml z-scores in OD, $D(22) = 0.225$, $p < 0.05$ and TtB ml scores in ON, $D(22) = 0.215$, $p < 0.05$, were both significantly non-normal.

	Kolmogorov-Smirnov					
	Healthy			Patients		
	Statistic	df	Sig.	Statistic	df	Sig.
Closed Dominant ap	.180	22	.062	.178	11	.200
Closed Non dominant ap	.160	22	.150	.118	11	.200
Opened Dominant ap	.141	22	.200	.139	11	.200
Opened Non dominant ap	.236	22	.002	.365	11	.000

Table 7: Kolmogorov-Smirnov test of normality for TtB ap data.

	Kolmogorov-Smirnov					
	Healthy			Patients		
	Statistic	df	Sig.	Statistic	df	Sig.
Closed Dominant ml	.160	22	.148	.226	11	.121
Closed Non dominant ml	.174	22	.081	.200	11	.200
Opened Dominant ap ml	.225	22	.005	.220	11	.145
Opened Non dominant ap	.215	22	.010	.212	11	.182

Table 8: Kolmogorov-Smirnov test of normality for TtB ml data.

1.3.2 Homogeneity of variance

The assumption of homogeneity of variance was checked using Leven's test which tests the null hypothesis that the variances in different groups are equal. TtB data were homogeneous as Levene's test was non-significant for TtB data (Table 9 and 10).

For the TtB ap scores, the variance were equal for healthy participants and patients with tennis elbow in all the conditions, $F(1,31) = 0.459$, $F(1,31) = 0.683$, $F(1,31) = 0.751$ and $F(1,31) = 0.214$ all were non significant.

For the TtB ml scores, the variance were equal for healthy participants and patients with tennis elbow in all the conditions, $F(1,31) = 0.346$, $F(1,31) = 0.710$, $F(1,31) = 0.057$ and $F(1,31) = 0.833$ all were non significant.

Test of Homogeneity of Variance Based on Mean				
	Levene Statistic	df1	df2	Sig.
Closed Dominant ap	.562	1	31	.459
Closed Non dominant ap	.170	1	31	.683
Opened Dominant ap	.103	1	31	.751
Opened Non dominant ap	1.612	1	31	.214

Table 9: Levene's test of homogeneity of variance for TtB ap data.

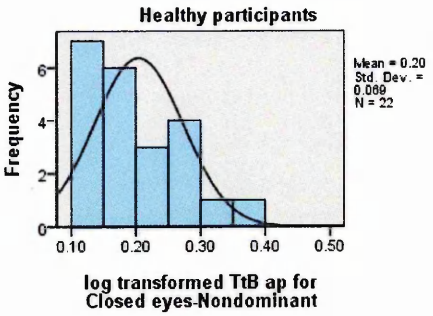
Test of Homogeneity of Variance Based on Mean				
	Levene Statistic	df1	df2	Sig.
Closed Dominant ml	.917	1	31	.346
Closed Non dominant ml	.141	1	31	.710
Opened Dominant ml	3.923	1	31	.057
Opened Non dominant ml	.045	1	31	.833

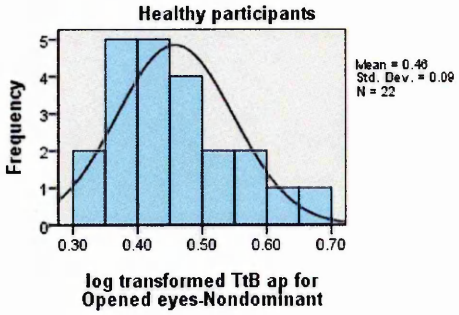
Table 10: Levene's test of homogeneity of variance for TtB ml data.

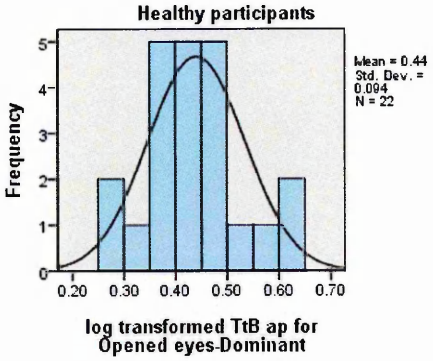
1.4 Checking the assumptions for log transformed TtB data

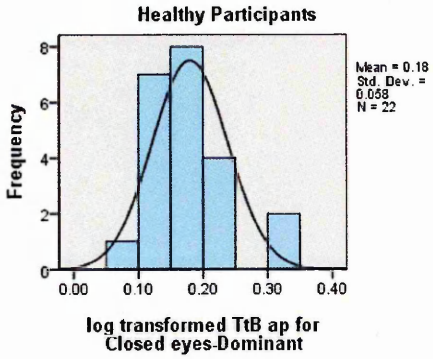
1.4.1 Normality

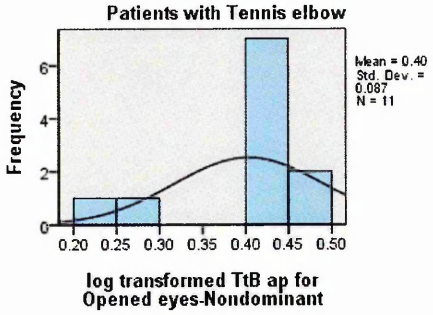
1.4.1.1 Histograms and Q-Q plots

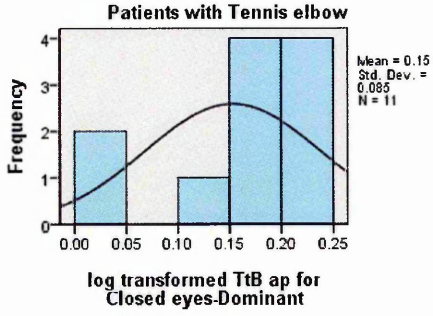












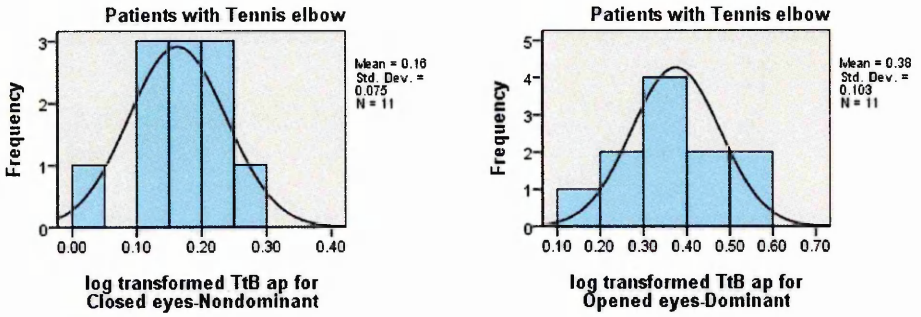
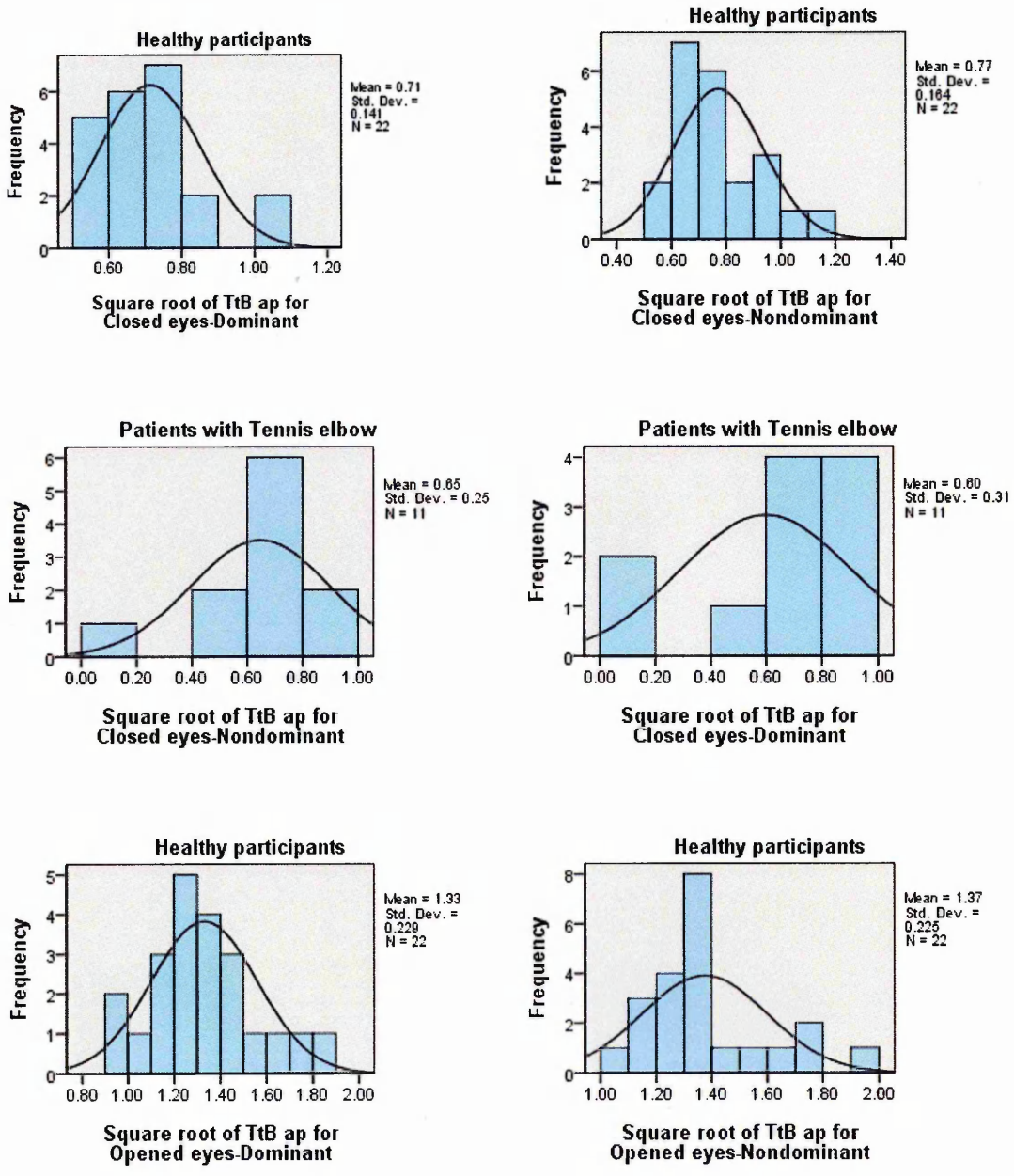


Figure 6: Distribution of TtB ap data after log transformation.



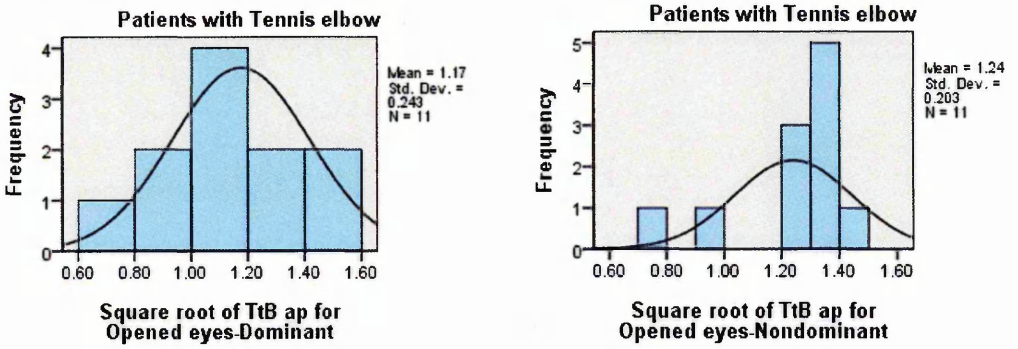
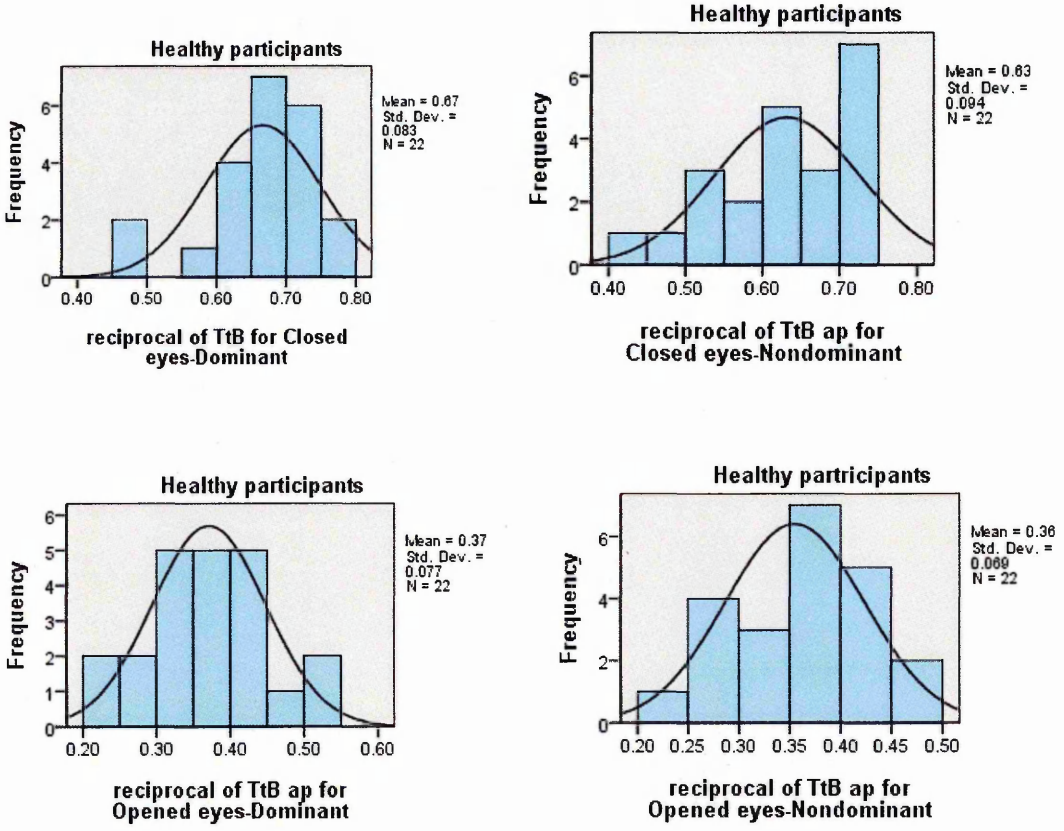


Figure 7: Distribution of TtB ap after square root transformation.



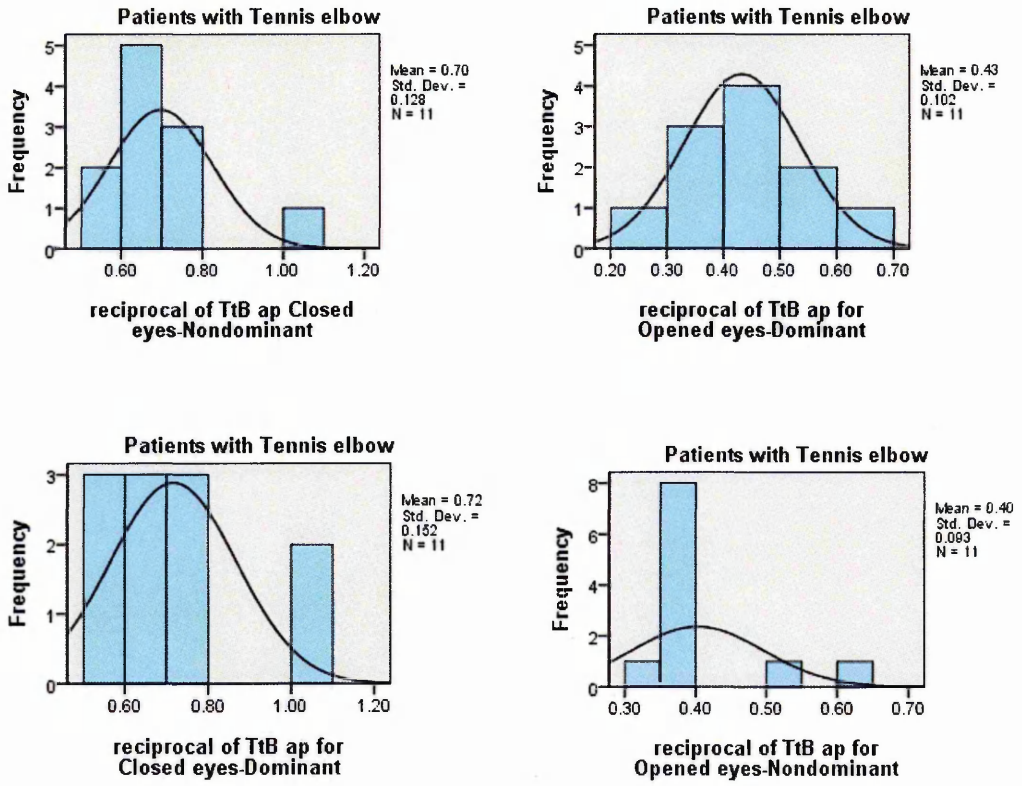


Figure 8: Distribution of TtB ap data after reciprocal transformation.

1.4.1.2 The Kolmogorov-Smirnov test

The log TtB ap scores in ON, $D(22) = 0.195$, $p < 0.05$ and log TtB ap scores in ON, $D(11) = 0.391$, $p < 0.001$, were both significantly non normal. The square root TtB ap scores in CD, $D(11) = 0.284$, $p < 0.05$, square root TtB ap scores in ON, $D(22) = 0.206$, $p < 0.05$ and square root TtB ap scores in ON $D(11) = 0.388$, $p < 0.001$, were all significantly non normal. The reciprocal TtB ap scores in ON, $D(11) = 0.413$, $p < 0.001$ were significantly non normal.

	Kolmogorov-Smirnov					
	Healthy			Patient		
	Statistic	df	Sig.	Statistic	df	Sig.
log transformed CD_ap	.153	22	.200	.215	11	.167
log transformed CN_ap	.133	22	.200	.135	11	.200
log transformed OD_ap	.104	22	.200	.103	11	.200
log transformed ON_ap	.195	22	.029	.391	11	.000

Table 11: Kolmogorov-Smirnov test of normality for TtB ap data after log transformation

	Kolmogorov-Smirnov					
	Healthy			Patient		
	Statistic	df	Sig.	Statistic	df	Sig.
sqr root CD_ap	.143	22	.200	.284	11	.013
sqr root CN_ap	.127	22	.200	.225	11	.125
sqr root OD_ap	.113	22	.200	.105	11	.200
sqr root ON_ap	.206	22	.016	.388	11	.000

Table 12: Kolmogorov-Smirnov test of normality for TtB ap data after square root transformation.

	Kolmogorov-Smirnov					
	Healthy			Patient		
	Statistic	df	Sig.	Statistic	df	Sig.
reciprocal trans CD_ap	.125	22	.200	.250	11	.053
reciprocal trans CN_ap	.124	22	.200	.160	11	.200
reciprocal trans OD_ap	.078	22	.200	.113	11	.200
reciprocal trans ON_ap	.154	22	.190	.413	11	.000

Table 13: Kolmogorov-Smirnov test of normality for TtB ap data after reciprocal transformation.

1.5 Mixed design ANOVA

Tests of Within-Subjects Effects Sphericity Assumed					
Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Eyes	40.351	1	40.351	177.720	.000
Eyes * Tennis_elbow	.491	1	.491	2.165	.151
Error(Eyes)	7.039	31	.227		
Dominance/Laterality	.265	1	.265	4.641	.039
Dominance/Laterality * Tennis_elbow	.003	1	.003	.056	.815
Error(Dominance/Laterality)	1.768	31	.057		
Eyes * Dominance/Laterality	.034	1	.034	.747	.394
Eyes * Dominance/Laterality * Tennis_elbow	.014	1	.014	.303	.586
Error(Eyes*Dominance/Laterality)	1.411	31	.046		

Table 14: Within subject effects for the TtB ap.

Tests of Between-Subjects Effects					
Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Tennis_elbow	.437	1	.437	3.192	.084
Error	4.240	31	.137		

Table 15: Between participants effects for TtB ap.

Tests of Within-Subjects Effects Sphericity Assumed					
Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Eyes	2.965	1	2.965	140.264	.000
Eyes * Tennis_elbow	.004	1	.004	.173	.680
Error(Eyes)	.655	31	.021		
Dominance/Laterality	.028	1	.028	3.275	.080
Dominance/Laterality * Tennis_elbow	.028	1	.028	3.267	.080
Error(Dominance/Laterality)	.266	31	.009		
Eyes * Dominance/Laterality	.013	1	.013	1.752	.195
Eyes * Dominance/Laterality * Tennis_elbow	.012	1	.012	1.619	.213
Error(Eyes* Dominance/Laterality)	.226	31	.007		

Table 16: Within subject effects for the TtB ml.

Tests of Between-Subjects Effects					
Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Tennis_elbow	.003	1	.003	.201	.657
Error	.397	31	.013		

Table 17: Between participants effects of TtB ml.

2 Response time data

2.1 Descriptive statistics

2.1.1 Response time data/ 1-choice response time and speed of movement in the upper limb

Healthy participants					
Descriptive statistics		**1-choiceRT Dominant upper limb**	**1-choiceSM Dominant upper limb**	**1-choiceRT Non dominant upper limb**	**1-choiceSM Non dominant upper limb**
Std. Error of Mean		.007	.064	.007	.034
Median		.274	.750	.271	.709
Mode		.324	.451	.267	.423
Variance		.001	.091	.001	.025
Minimum		.228	.451	.198	.423
Maximum		.337	1.860	.324	1.091
Percentiles	25	.247	.667	.258	.684
	50	.274	.750	.271	.709
	75	.292	1.019	.287	.833

Table 18: Descriptive statistics for 1-choice response time and speed of movement in healthy participants.

Patients with Tennis elbow					
Descriptive statistics		**1-choiceRT Affected upper limb**	**1-choiceSM Affected upper limb**	**1-choiceRT Non Affected upper limb**	**1-choiceSM Non Affected upper limb**
Std. Error of Mean		.010	.251	.0133	.155
Median		.296	.897	.254	.857
Mode		.233	.426	.213	.288
Variance		.001	.693	.002	.263
Minimum		.233	.426	.213	.288
Maximum		.336	3.333	.346	2.212
Percentiles	25	.248	.691	.229	.757
	50	.296	.897	.254	.857
	75	.315	1.519	.303	1.176

Table 19: Descriptive statistics for 1-choice response time and speed of movement in the upper limb in patients with tennis elbow

2.1.2 Response time data/ 1-choice response time and speed of movement in the lower limb

Healthy participants					
Descriptive statistics		1-choiceRT Dominant lower limb	1-choiceSM Dominant lower limb	1-choiceRT Non dominant lower limb	1-choiceSM Non dominant lower limb
Mean		.275	.928	.274	.894
Std. Error of Mean		.009	.048	.006	.039
Median		.267	.934	.280	.866
Mode		.218	.738	.205	.573
Std. Deviation		.041	.227	.028	.182
Variance		.002	.051	.001	.033
Minimum		.218	.513	.205	.573
Maximum		.379	1.326	.330	1.326
Percentiles	25	.247	.735	.254	.759
	50	.267	.937	.280	.866
	75	.288	1.109	.294	.998

Table 20: Descriptive statistics for 1-choice response time and speed of movement in the lower limb in healthy participants

Patients with Tennis elbow					
Descriptive statistics		1-choiceRT Ipsilateral lower limb	1-choiceSM Ipsilateral lower limb	1-choiceRT Contralateral lower limb	1-choiceSM Contralateral lower limb
Mean		.268	.865	.284	.905
Std. Error of Mean		.014	.089	.018	.123
Median		.255	.815	.274	.870
Mode		.216	.459	.225	.407
Std. Deviation		.045	.296	.059	.409
Variance		.002	.088	.003	.167
Minimum		.216	.459	.225	.407
Maximum		.371	1.468	.450	1.912
Percentiles	25	.241	.583	.256	.593
	50	.255	.815	.274	.870
	75	.285	1.098	.286	1.046

Table 21: Descriptive statistics for 1-choice response time and speed of movement in the upper limb patients with Tennis elbow

2.1.3 Response time data/ 2-choice response time and speed of movement in the upper limb

Descriptive statistics		2-choiceRT Dominant upper limb/ same side	2-choiceRT Dominant upper limb/ other side	2-choiceRT Non dominant upper limb/ same side	2-choiceRT Non dominant upper limb/ other side
Std. Error of Mean		.008	.013	.010	.0113
Median		.312	.31200	.294	.326
Mode		.296	.299	.289	.256
Variance		.002	.004	.002	.003
Minimum		.248	.249	.204	.256
Maximum		.403	.484	.430	.476
Percentiles	25	.299	.298	.279	.298
	50	.312	.312	.294	.326
	75	.354	.354	.341	.369

Table 22: Descriptive statistics for 2-choice response time the upper limb in healthy participants

Descriptive statistics		2-choiceSM Dominant upper limb/ same side	2-choiceSM Dominant upper limb/ other side	2-choiceSM Non dominant upper limb/ same side	2-choiceSM Non dominant upper limb/ other side
Std. Error of Mean		0.053	0.047	0.040	0.043
Median		0.831	0.724	0.763	0.677
Mode		0.798	0.847	0.784	0.427
Variance		0.061	0.049	0.036	0.041
Minimum		0.466	0.376	0.480	0.427
Maximum		1.410	1.131	1.151	1.379
Percentiles	25	0.766	0.567	0.698	0.568
	50	0.831	0.724	0.763	0.677
	75	1.049	0.883	0.894	0.771

Table 23: Descriptive statistics for 2-choice speed of movement in the upper limb in healthy participants

Descriptive statistics		2-choiceRT Affected upper limb/ same side	2-choiceRT Affected upper limb/ other side	2-choiceRT Non Affected upper limb/ same side	2-choiceRT Non Affected upper limb/ other side
Std. Error of Mean		0.016	0.012	0.014	0.019
Median		0.293	0.304	0.282	0.289
Mode		0.335	0.240	0.246	0.334
Variance		0.003	0.002	0.002	0.004
Minimum		0.229	0.240	0.246	0.210
Maximum		0.395	0.369	0.386	0.438
Percentiles	25	0.261	0.284	0.258	0.270
	50	0.293	0.304	0.282	0.289
	75	0.335	0.354	0.354	0.334

Table 24: Descriptive statistics of 2-choice response time in the upper limb in patients with Tennis elbow

Descriptive statistics		2-choiceSM Affected upper limb/ same side	2-choiceSM Affected upper limb/ other side	2-choiceSM Non Affected upper limb/ same side	2-choiceSM Non Affected upper limb/ other side
Std. Error of Mean		0.144	0.179	0.147	0.127
Median		1.046	0.874	1.096	0.933
Mode		0.582	0.492	0.423	0.428
Variance		0.228	0.351	0.238	0.177
Minimum		0.582	0.492	0.423	0.428
Maximum		2.177	2.286	2.119	1.939
Percentiles	25	0.746	0.699	0.573	0.598
	50	1.046	0.874	1.096	0.933
	75	1.502	1.311	1.296	1.127

Table 25: Descriptive statistics of 2-choice speed of movement in the upper limb in patients with Tennis elbow

2.1.4 Response time data/ 2-choice response time and speed of movement in the lower limb

Descriptive statistics		2-choiceRT Dominant lower limb/ same side	2-choiceRT Dominant lower limb/ other side	2-choiceRT Non dominant lower limb/ same side	2-choiceRT Non dominant lower limb/ other side
Std. Error of Mean		0.010	0.009	0.012	0.011
Median		0.297	0.308	0.332	0.309
Mode		0.237	0.273	0.214	0.235
Variance		0.002	0.002	0.003	0.003
Minimum		0.237	0.262	0.214	0.235
Maximum		0.419	0.425	0.424	0.456
Percentiles	25	0.272	0.276	0.293	0.288
	50	0.297	0.308	0.332	0.309
	75	0.343	0.340	0.376	0.353

Table 26: Descriptive statistics for 2-choice response time in the lower limb in healthy participants.

Descriptive statistics		2-choiceSM Dominant lower limb/ same side	2-choiceSM Dominant lower limb/ other side	2-choiceSM Non dominant lower limb/ same side	2-choiceSM Non dominant lower limb/ other side
Std. Error of Mean		0.047	0.040	0.040	0.033
Median		0.807	0.715	0.797	0.761
Mode		0.722	0.435	0.492	0.493
Variance		0.048	0.035	0.035	0.023
Minimum		0.506	0.435	0.492	0.493
Maximum		1.190	1.127	1.208	1.088
Percentiles	25	0.667	0.626	0.713	0.656
	50	0.807	0.715	0.797	0.761
	75	1.038	0.897	0.905	0.872

Table 27: Descriptive statistics for 2-choice speed of movement in the lower limb in healthy participants

Descriptive statistics		2-choiceRT Ipsi-lateral lower limb/ same side	2-choiceRT Ipsi-lateral lower limb/ other side	2-choiceRT Contra-lateral lower limb/ same side	2-choiceRT Contra-lateral lower limb/ other side
Std. Error of Mean		0.015	0.019	0.021	0.028
Median		0.283	0.306	0.210	0.311
Mode		0.244	0.255	0.237	0.235
Variance		0.003	0.004	0.005	0.009
Minimum		0.244	0.255	0.237	0.235
Maximum		0.396	0.460	0.492	0.586
Percentiles	25	0.260	0.286	0.280	0.272
	50	0.283	0.306	0.210	0.311
	75	0.308	0.349	0.367	0.344

Table 28: Descriptive statistics for 2-choice response time in the lower limb in patients with Tennis elbow

Descriptive statistics		2-choiceSM Ipsi-lateral lower limb/ same side	2-choiceSM Ipsi-lateral lower limb/ other side	2-choiceSM Contra-lateral lower limb/ same side	2-choiceSM Contra-lateral lower limb/ other side
Std. Error of Mean		0.088	0.118	0.170	0.052
Median		0.818	0.711	0.882	0.714
Mode		0.526	0.466	0.481	0.403
Variance		0.086	0.152	0.317	0.030
Minimum		0.526	0.466	0.481	0.403
Maximum		1.616	1.778	2.602	0.964
Percentiles	25	0.786	0.638	0.668	0.556
	50	0.818	0.711	0.882	0.714
	75	0.985	0.886	0.994	0.829

Table 29: Descriptive statistics for 2-choice speed of movement in the lower limb in patients with Tennis elbow

Outliers in the 1-choice response time and speed of movement in the upper Limb

Before performing any statistical analysis, the 1-choice RT and SM upper limb data were plotted using simple box plots so outliers could be identified (Figure 9). Only one outlier was identified in the 1-choice SM of the affected upper limb in the patients group.

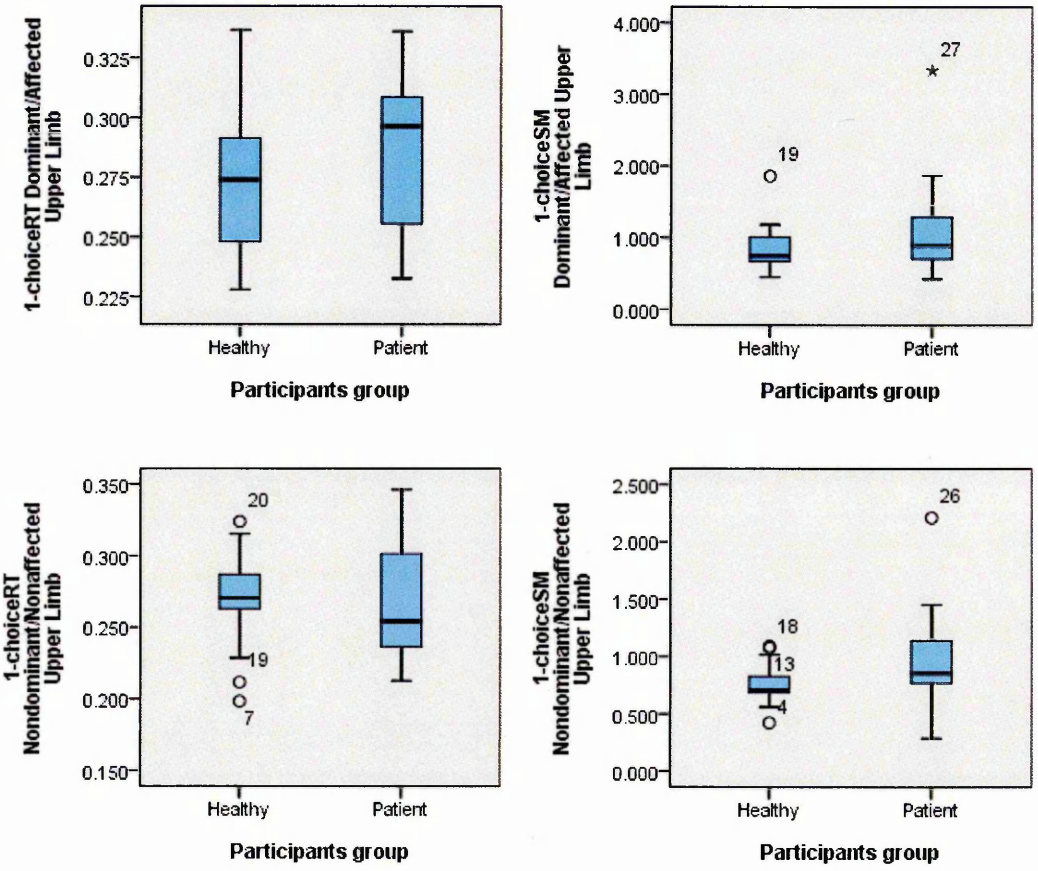


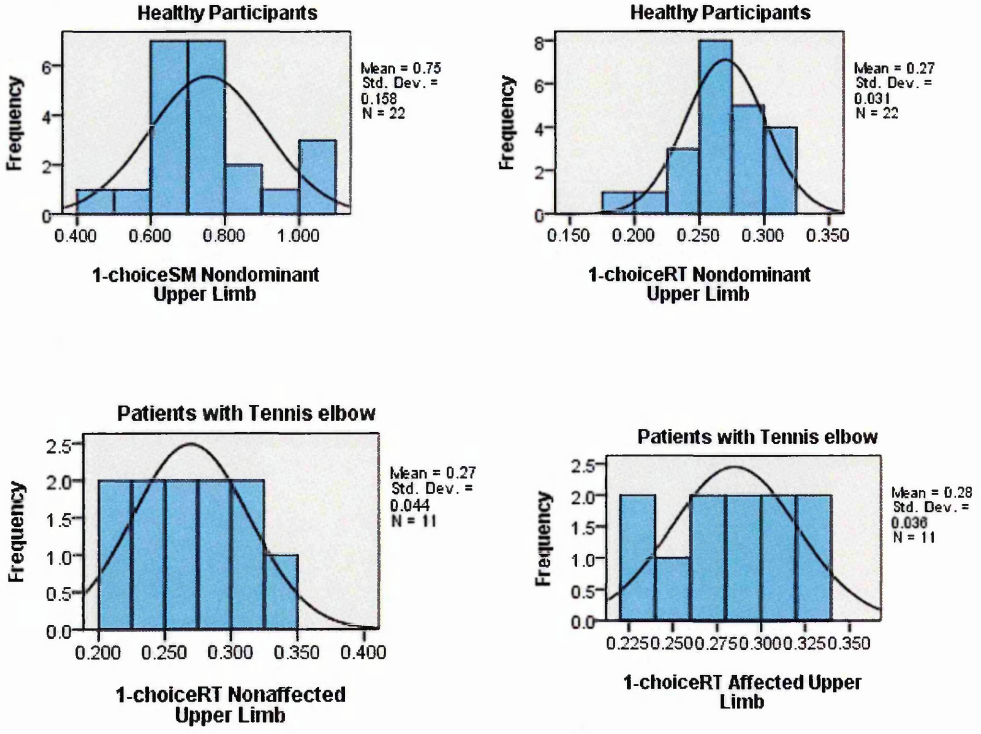
Figure 9: Box plots for 1-choice response time and speed of movement in healthy participants and patients with Tennis elbow.

2.2 Checking the assumptions of the 1-choice response time and speed of movement in the upper Limb

2.2.1 Normality

2.2.1.1 Histograms and Q-Q plots

To check the assumption of normality, the 1-choice RT and SM in the upper limb data were plotted using Q-Q plots and histograms (Figure 10-11). The histograms were visually checked for skeweness and kurtosis, in healthy participants the 1-choice RT of the dominant upper limb is slightly positively skewed while the 1-choice SM of the affected upper limb in patients with tennis elbow is platykurtic (negative kurtosis) (Figure 10).



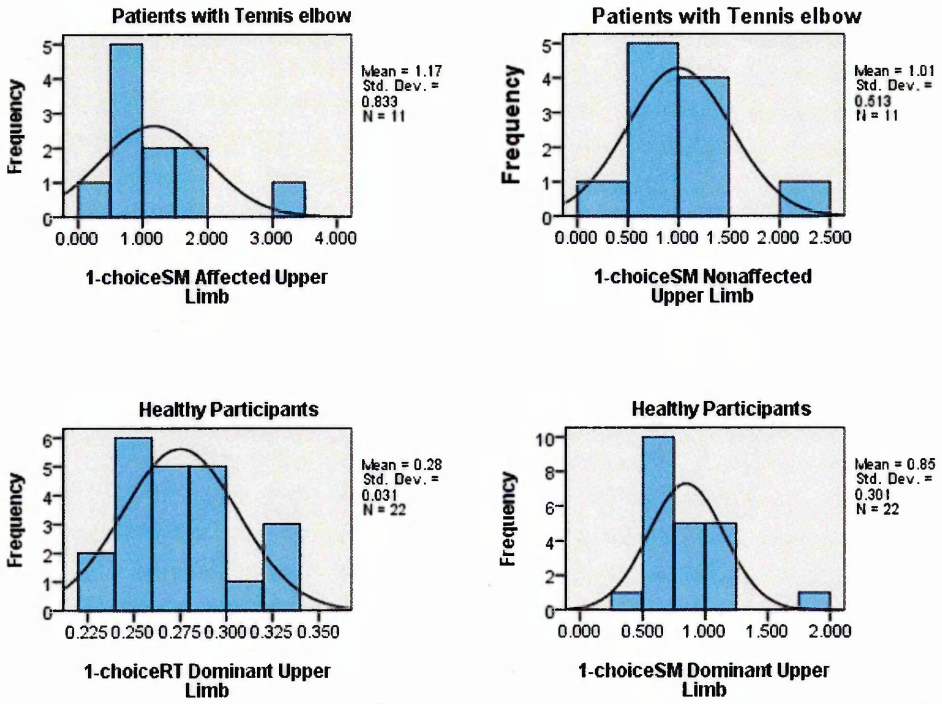
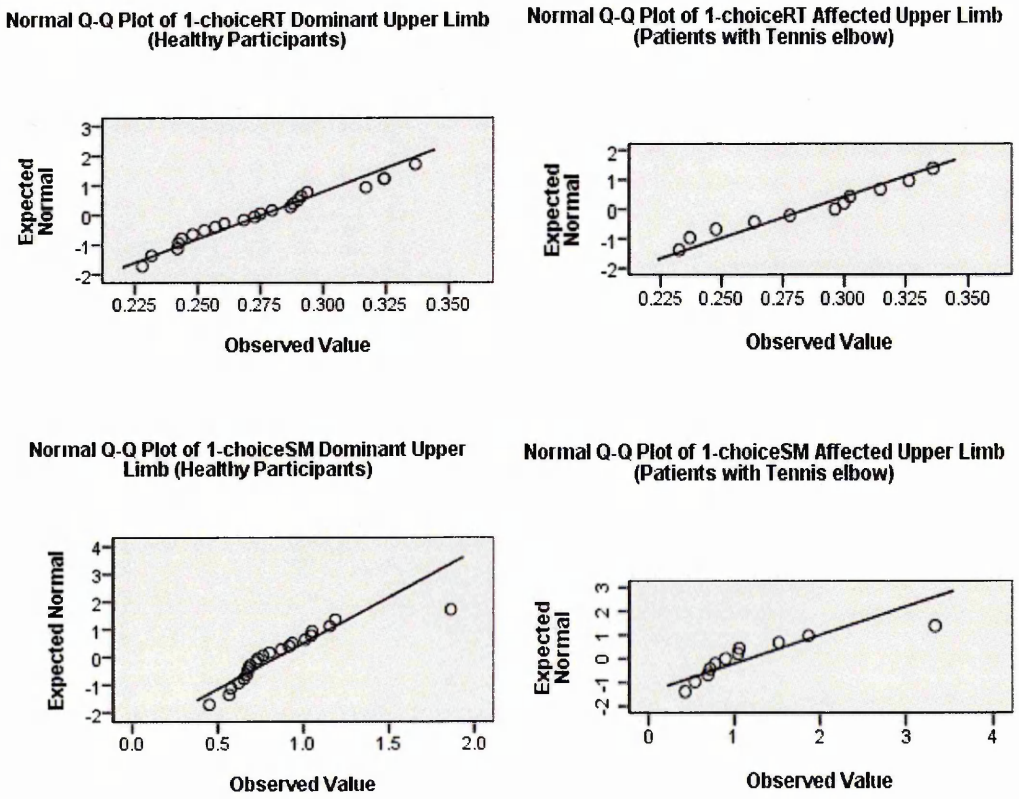


Figure 10: Histograms for 1-choice response time and speed of movement in healthy participants and patients with Tennis elbow



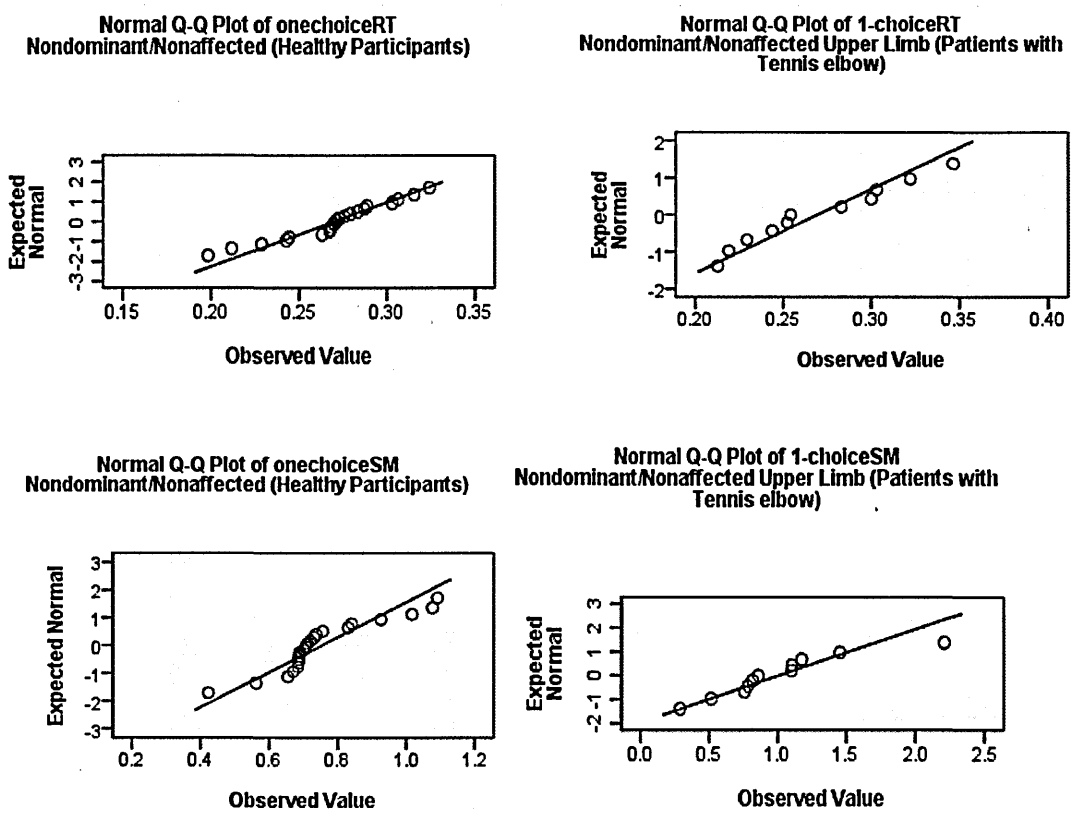


Figure 11: Q-Q plots for 1-choice response time and speed of movement.

2.2.1.2 Skewness and Kurtosis scores and their z-scores

	Healthy Participants			
	1-choiceRT Dominant upper limb	1-choiceSM Dominant upper limb	1-choiceRT Non dominant upper limb	1-choiceSM Non dominant upper limb
Skewness	.389	1.888	-.566	.655
Std. Error of Skewness	.491	.491	.491	.491
z skewness	.792	3.845	1.153	1.334
Kurtosis	-.714	5.200	.531	.888
Std. Error of Kurtosis	.953	.953	.953	.953
z kurtosis	0.749	5.456	0.557	0.932

Table 30: Skewness and Kurtosis scores for 1-choice response time and speed of movement in healthy participants.

Patients with Tennis elbow				
	1-choiceRT Affected upper limb	1-choiceSM Affected upper limb	1-choiceRT Non affected upper limb	1-choiceSM Non affected upper limb
Skewness	-.199	2.025	.366	1.202
Std. Error of Skewness	.661	.661	.661	.661
z skewness	0.301	3.064	0.554	1.818
Kurtosis	-1.304	4.513	-1.045	2.430
Std. Error of Kurtosis	1.279	1.279	1.279	1.279
z kurtosis	1.02	3.529	0.817	1.9

Table 31: Skewness and Kurtosis scores for 1-choice response time and speed of movement in patients with Tennis elbow.

After ignoring the minus sign, values of *z*-scores greater than 1.96 are significant at $p<0.05$. *z*-scores that are significantly skewed or kurtosis are highlighted in grey (Table 30 and 31).

2.2.1.3 The Kolmogorov-Smirnov test

In the healthy control group, the 1-choice RT and SM of the non dominant upper limb, $D(22) = 0.194$, $p < 0.05$ and $D(22) = 0.223$, $p < 0.05$ were both significantly non normal. While in the patients group, the 1-choice SM of the affected upper limb, $D(11) = 0.281$, $p < 0.05$.

	Kolmogorov-Smirnov					
	Healthy			Patients		
	Statistic	df	Sig.	Statistic	df	Sig.
1-choiceRT Dominant/Affected upper limb	.096	22	.200	.170	11	.200
1-choiceSM Dominant/Affected upper limb	.153	22	.197	.281	11	.015
1-choiceRT Non dominant/Non affected upper limb	.194	22	.030	.181	11	.200
1-choiceSM Non dominant/Non affected upper limb	.223	22	.006	.188	11	.200

Table 32: Kolmogorov-Smirnov test of normality for 1-choice response time and speed of movement

2.2.2 Homogeneity of variance

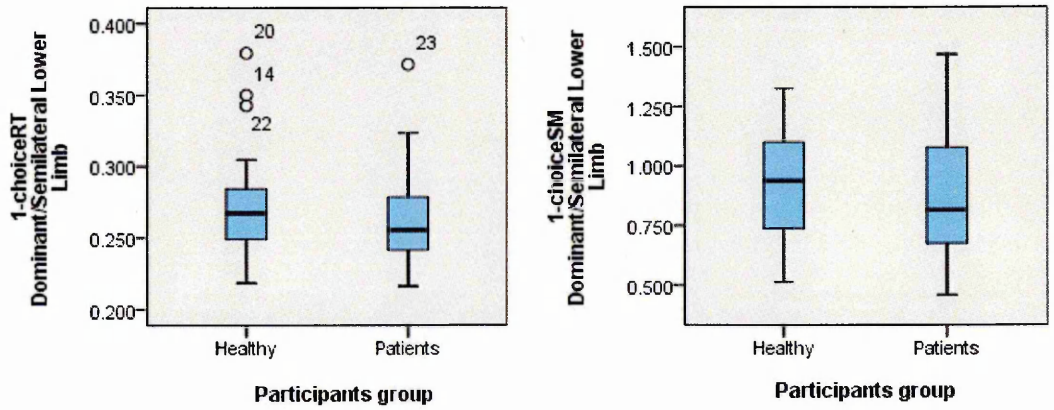
For the 1-choice SM of the dominant or affected upper limb, the variances were significantly different in the two groups, $F(1,31) = 7.531$, $p < 0.05$. The variances were also significantly different in the two groups for the 1-choice RT and 1-choice SM of the non dominant or affected upper limb, $F(1,31) = 4.176$, $p < 0.05$ and $F(1,31) = 10.469$, $p < 0.01$ respectively. (Table 33).

Test of Homogeneity of Variance Based on Mean				
	Levene Statistic	df1	df2	Sig.
1-choiceRT Dominant Affected upper limb	.553	1	31	.463
1-choiceSM Dominant Affected upper limb	7.531	1	31	.010
1-choiceRT Non dominant/ Non affected upper limb	4.176	1	31	.050
1-choiceSM Non dominant/ Non affected upper limb	10.469	1	31	.003

Table 33: Levene's test of homogeneity of variance for 1-choice response time and speed of movement.

2.3 Outliers in the 1-choice response time and speed of movement in the lower limb

Prior to performing any statistical analysis, the 1-choice RT and SM data were plotted using simple box plots so outliers could be identified (Figure 12). Only one outlier was identified in the 1-choice RT of the contra-lateral lower limb in the patients group. Similar to the debate earlier in the TtB data, this outlier could not be removed because it came from the patients group who were representative sample of the population of interest and this extreme value might reflect the chronicity of the condition.



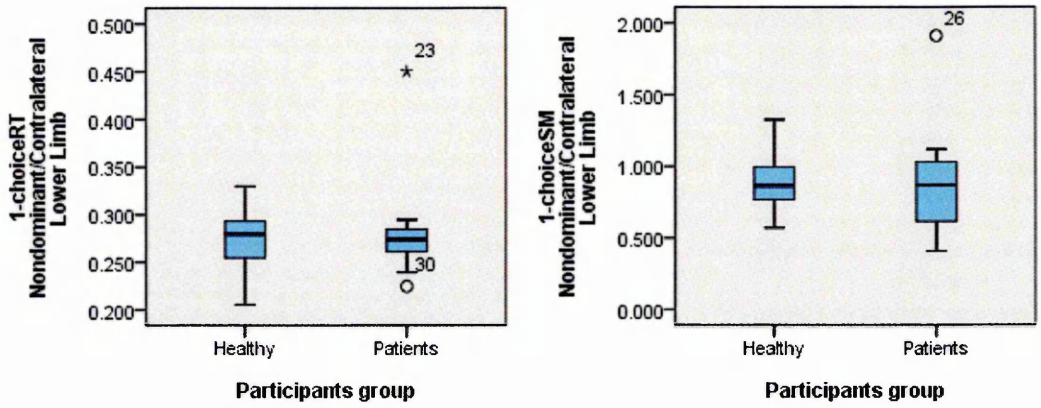


Figure 12: Box plots for 1-choice response time and speed of movement in the lower limb.

2.4 Checking the assumptions of the 1-choice response time and speed of movement in the lower limb

2.4.1 Normality

2.4.1.1 Histograms and Q-Q plots

The 1-choice RT and SM data in the lower limb was plotted using Q-Q plots and histograms (Figure 13-14). The histograms were visually checked for skeweness and kurtosis, the 1-choice RT of the dominant lower limb in healthy participants and the 1-choice SM of the semi-lateral lower limb in patients with tennis elbow were slightly positively skewed. While the 1-choice RT of the semi-lateral and contra-lateral lower limb in patients with tennis elbow looks platykurtic (negative kurtosis) (Figure 13).

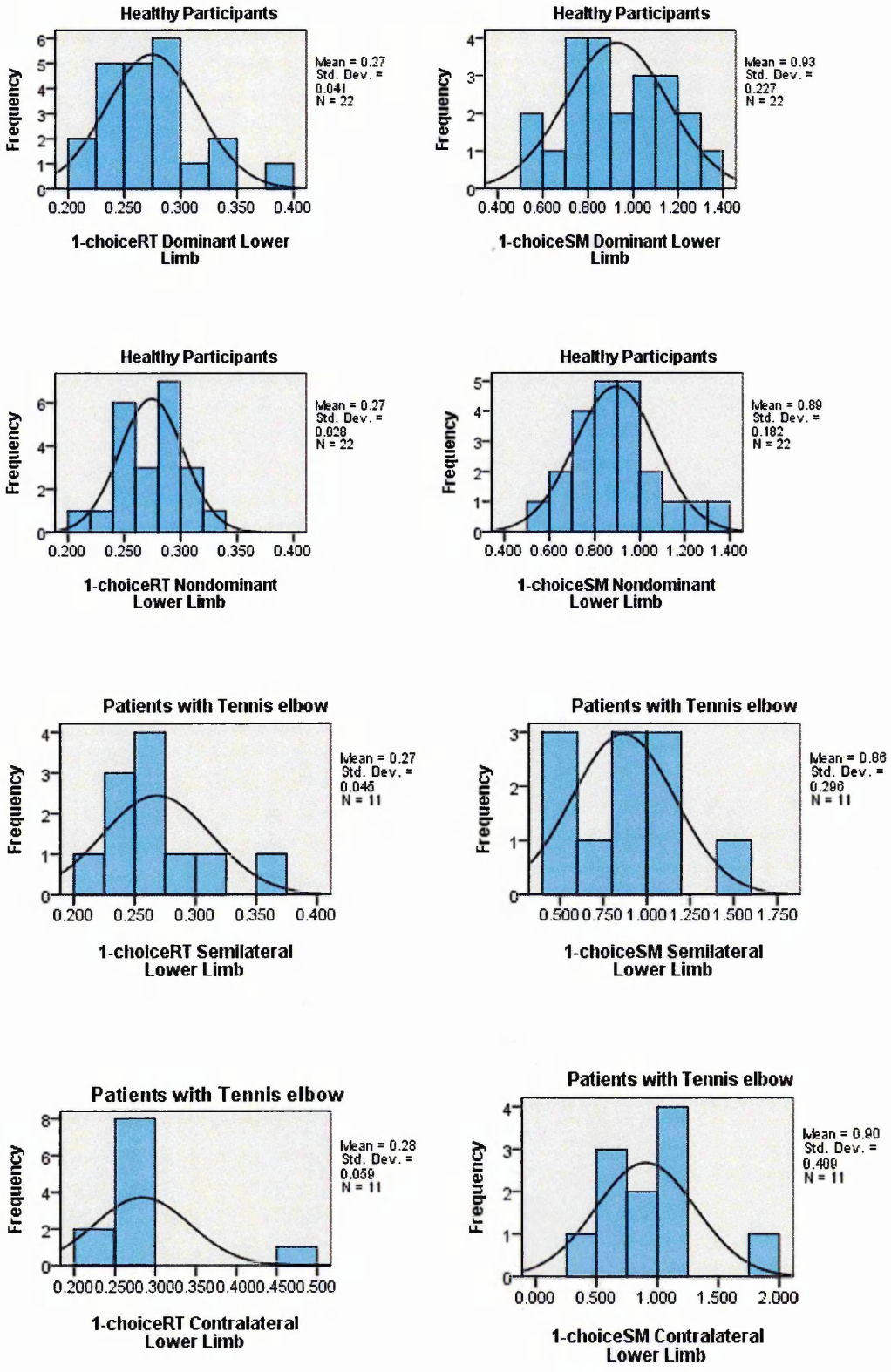


Figure 13: Histograms for 1-choice response time and speed of movement in the lower limb

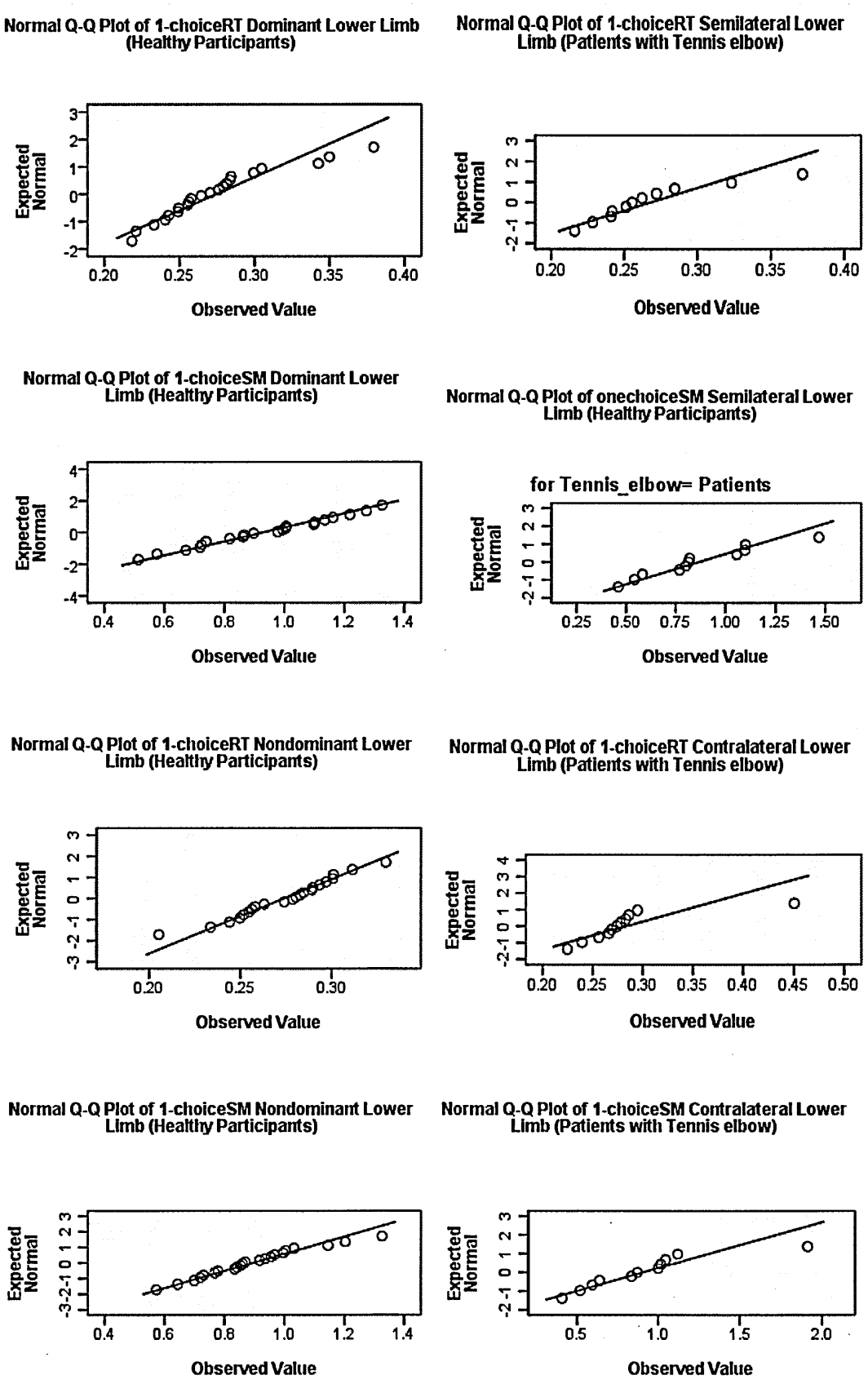


Figure 14: Q-Q plots for 1-choice response time and speed of movement in the lower limb.

2.4.1.2 Skewness and Kurtosis scores and their z-scores

Healthy Participants				
	1-choiceRT Dominant/ Semi-lateral lower limb	1-choiceSM Dominant/ Semi-lateral lower limb	1-choiceRT Non dominant/ Contra-lateral lower limb	1-choiceSM Non dominant/ Contra-lateral lower limb
Skewness	1.077	-.017	-.385	.545
Std. Error of Skewness	.491	.491	.491	.491
z skewness	2.193	0.034	0.784	1.11
Kurtosis	.999	-.862	.387	.358
Std. Error of Kurtosis	.953	.953	.953	.953
z kurtosis	1.048	0.905	0.406	0.376

Table 34: Skewness and kurtosis for 1-choice response time and speed of movement in the lower limb in healthy participants.

Patients with Tennis elbow				
	1-choiceRT Dominant/ Semi-lateral lower limb	1-choiceSM Dominant/ Semi-lateral lower limb	1-choiceRT Non dominant/ Contra-lateral lower limb	1-choiceSM Non dominant/ Contra-lateral lower limb
Skewness	1.388	.602	2.566	1.439
Std. Error of Skewness	.661	.661	.661	.661
z skewness	2.1	0.911	3.882	2.177
Kurtosis	1.872	.221	7.779	3.232
Std. Error of Kurtosis	1.279	1.279	1.279	1.279
z kurtosis	1.464	0.173	6.082	2.527

Table 35: Skewness and kurtosis for 1-choice response time and speed of movement in the lower limb in healthy participants.

After ignoring the minus sign, values of *z*-scores greater than 1.96 are significant at $p<0.05$. *z*-scores that are significantly skewed or kurtosis are highlighted in grey (Table 34-35).

2.4.1.3 The Kolmogorov-Smirnov test

The 1-choice RT of the contra-lateral lower limb in the patients group, $D(11) = .335$, $p<0.01$ was significantly non normal. (Table 36).

	Kolmogorov-Smirnov					
	Healthy			Patients		
	Statistic	df	Sig.	Statistic	df	Sig.
1-choiceRT Dominant/Semi-lateral lower limb	.178	22	.069	.189	11	.200
1-choiceSM Dominant/ Semi-lateral lower limb	.117	22	.200	.196	11	.200
1-choiceRT Non dominant/ Contra-lateral lower limb	.111	22	.200	.335	11	.001
1-choiceSM Non dominant/ Contra-lateral lower limb	.098	22	.200	.210	11	.192

Table 36: Kolmogorov-Smirnov test of normality for 1-choice response time and speed of movement in the lower limb.

2.4.2 Homogeneity of variance

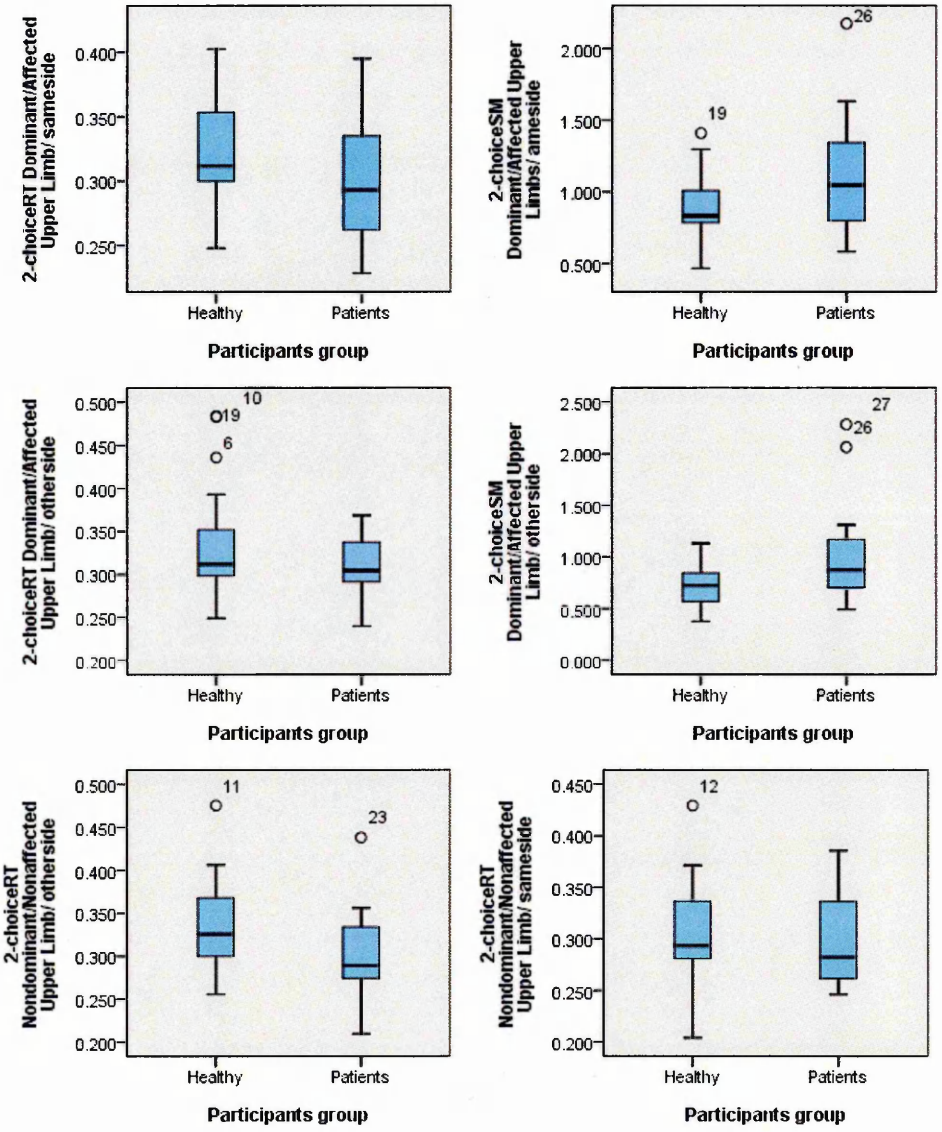
For the 1-choice SM of the non dominant or contra-lateral lower limb, the variances were significantly different in the two groups, $F(1,31) = 6.576$, $p < .05$. (Table 37).

Test of Homogeneity of Variance Based on Mean				
	Levene Statistic	df1	df2	Sig.
1-choiceRT Dominant/ Semi-lateral lower limb	.045	1	31	.833
1-choiceSM Dominant/ Semi-lateral lower limb	.602	1	31	.444
1-choiceRT Non dominant/ Contra-lateral lower limb	.281	1	31	.600
1-choiceSM Non dominant/ Contra-lateral lower limb	6.576	1	31	.015

Table 37: Levene's test of homogeneity of variance for 1-choice response time and speed of movement in the lower limb.

2.5 Outliers in the 2-choice response time and speed of movement in the upper Limb

Prior to perform any statistical analysis, the 2-choice RT and SM data were plotted using simple box plots so outliers could be identified. Only one outlier was identified in the 2-choice SM of the non dominant upper limb in the healthy group (Figure 15).



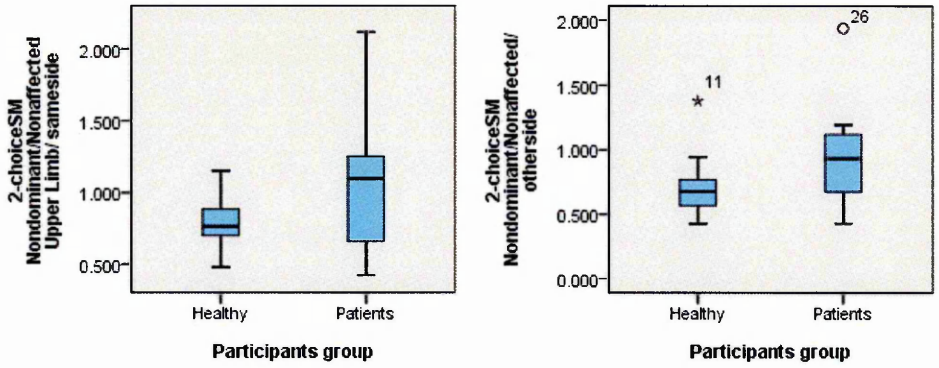


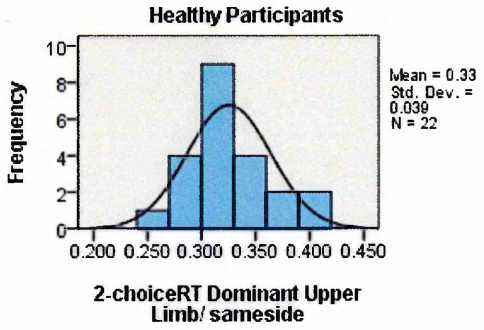
Figure 15: Box plots for 2-choice response time and speed of movement in the upper limb.

2.6 Checking the assumptions of the 2-choice response time and speed of movement in the upper Limb

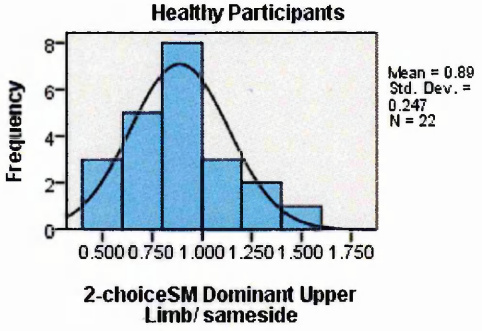
2.6.1 Normality

2.6.1.1 Histograms and Q-Q plots

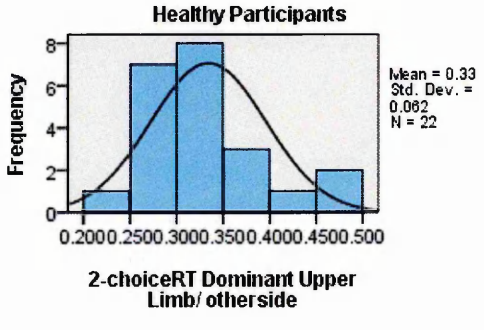
The 2-choice RT and SM data in the upper limb was plotted using Q-Q plots and histograms (Figure 16-17). The histograms were visually checked for skeweness and kurtosis, positive skew could be seen in 2-choice RT non dominant upper limb/ other side (Healthy participants), 2-choice SM non dominant upper limb/ other side (Healthy participants), 2-choice SM affected upper limb/ same side (patients with tennis elbow). On the other hand, platykurtic (negative kurtosis) was shown in the 2-choice RT affected upper limb/ same side (patients with tennis elbow), 2-choice SM affected upper limb/ other side (patients with tennis elbow) and the 2-choice SM non affected upper limb/ same side (patients with tennis elbow). (Figure 16).



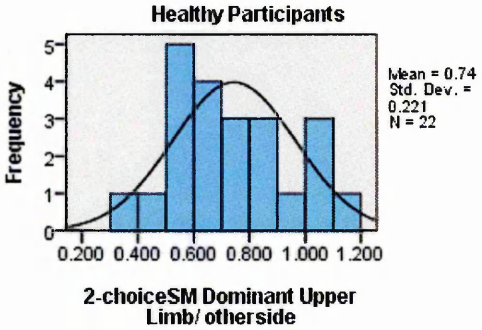
2-choiceRT Dominant Upper Limb/ sameside



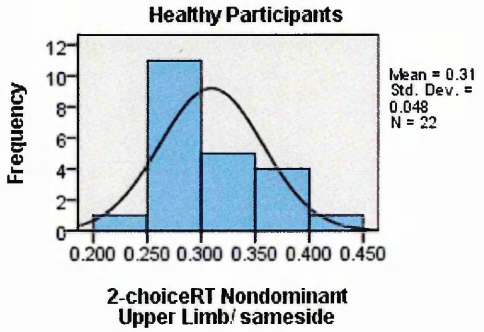
2-choiceSM Dominant Upper Limb/ sameside



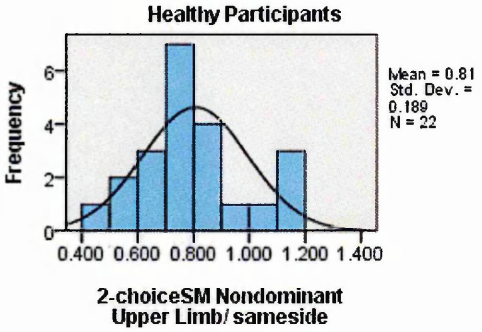
2-choiceRT Dominant Upper Limb/ otherside



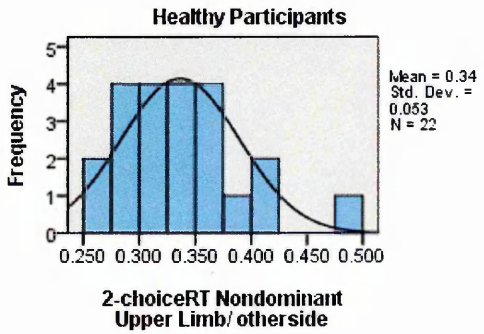
2-choiceSM Dominant Upper Limb/ otherside



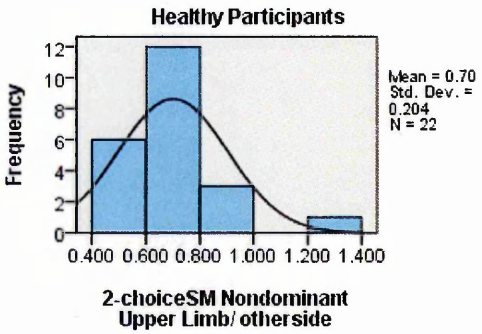
2-choiceRT Nondominant Upper Limb/ sameside



2-choiceSM Nondominant Upper Limb/ sameside



2-choiceRT Nondominant Upper Limb/ otherside



2-choiceSM Nondominant Upper Limb/ otherside

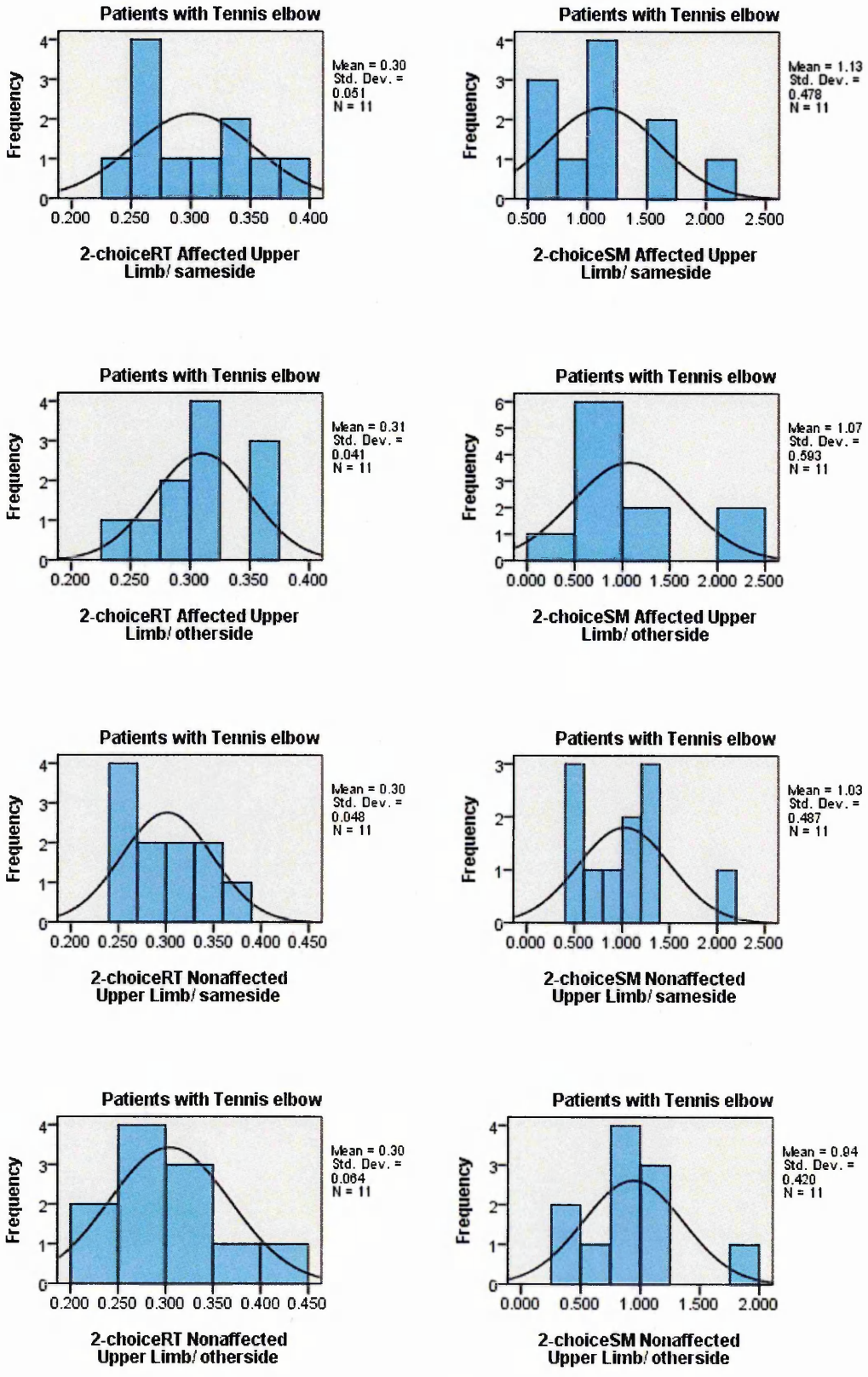
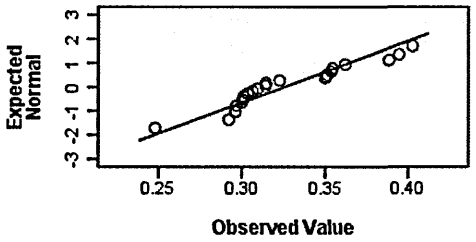
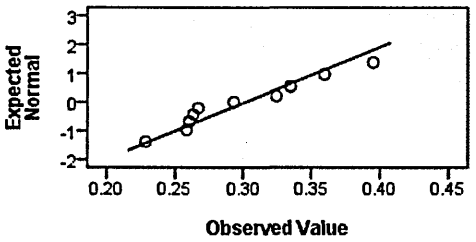


Figure 16: Histograms for 2-choice response time and speed of movement in the upper limb.

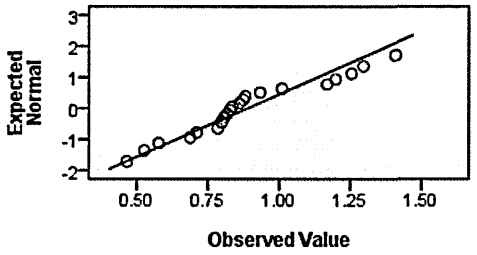
Normal Q-Q Plot of 2-choiceRT Dominant Upper Limb/ sameside (Healthy Participants)



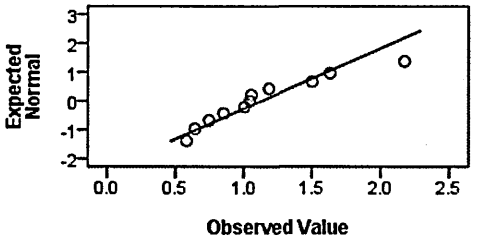
Normal Q-Q Plot of 2-choiceRT Affected Upper Limb/ sameside (Patients with Tennis elbow)



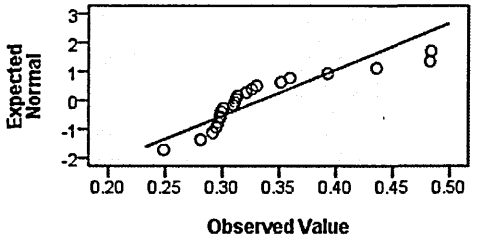
Normal Q-Q Plot of 2-choiceSM Dominant Upper Limb/ sameside (Healthy Participants)



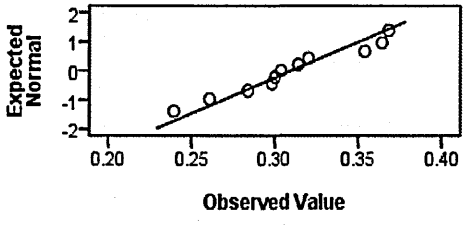
Normal Q-Q Plot of twochoiceSM Affected Upper Limb/ sameside (Patients with Tennis elbow)



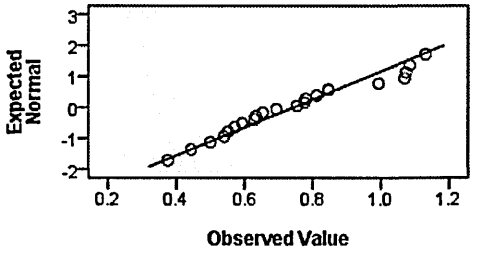
Normal Q-Q Plot of 2-choiceRT Dominant Upper Limb/ otherside (Healthy Participants)



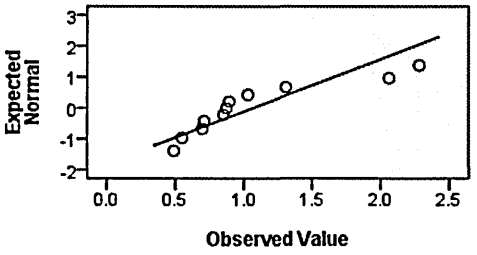
Normal Q-Q Plot of 2-choiceRT Affected Upper Limb/ otherside (Patients with Tennis elbow)



Normal Q-Q Plot of 2-choiceSM Dominant Upper Limb/ otherside (Healthy Participants)



Normal Q-Q Plot of 2-choiceSM Affected Upper Limb/ otherside (Patients with Tennis elbow)



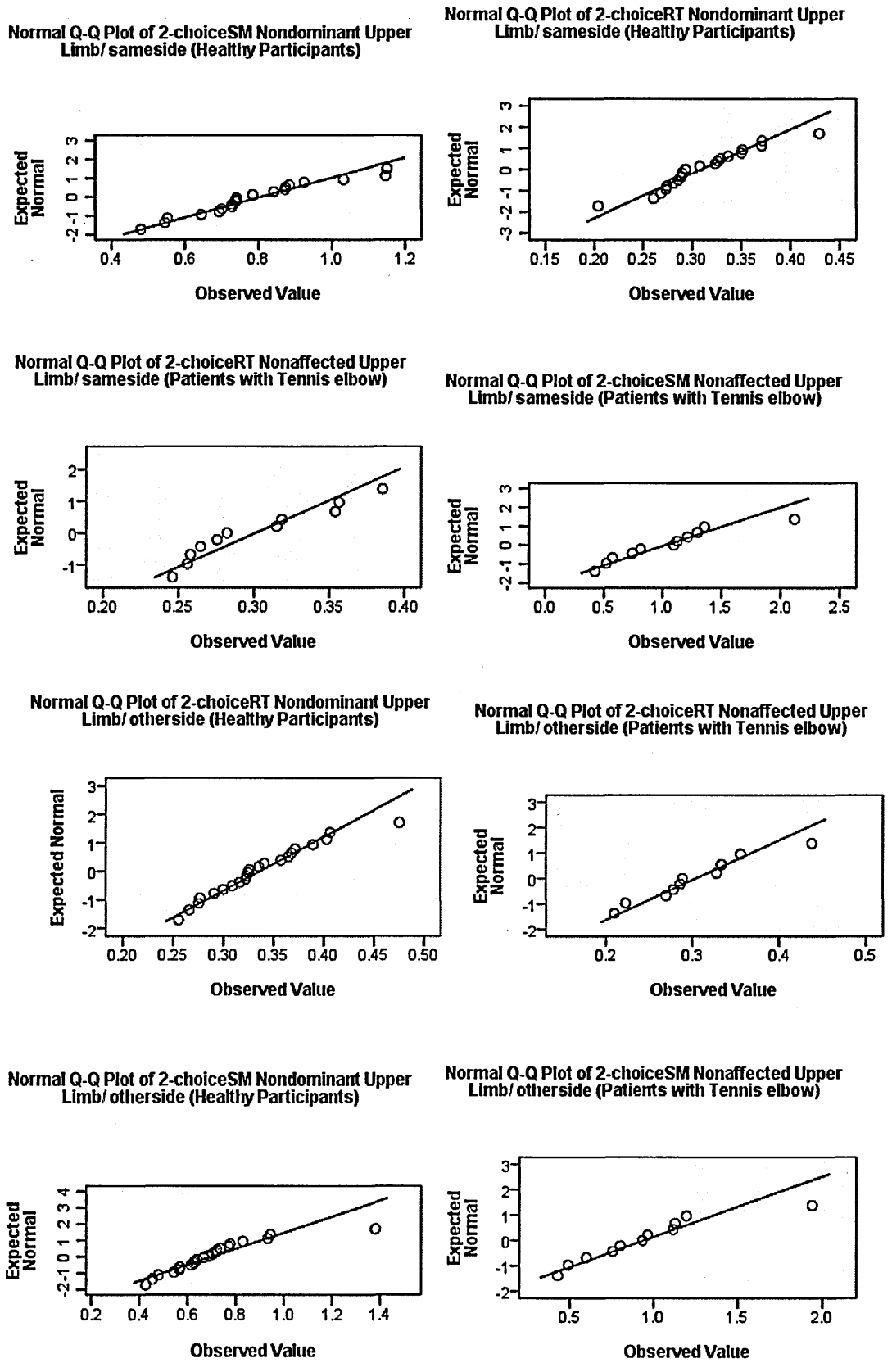


Figure 17: Q-Q plots for 2-choice response time and speed of movement in the upper limb.

2.6.1.2 Skewness and Kurtosis scores and their z-scores

	2-choiceRT Dominant upper limb/ sameside	2-choiceRT Dominant upper limb/ otherside	2-choiceRT Non dominant upper limb/ sameside	2-choiceRT Non dominant upper limb/ otherside
Skewness	0.469	1.489	0.437	0.740
Std. Error of	0.491	0.491	0.491	0.491
z skewness	0.955	3.033	0.890	1.507
Kurtosis	-0.193	1.592	1.168	0.791
Std. Error of Kurtosis	0.953	0.953	.953	0.953
z kurtosis	0.203	1.671	1.226	0.830

Table 38: Skewness and kurtosis for 2-choice response time in the upper limb in healthy participants

	2-choiceSM Dominant upper limb/ same side	2-choiceSM Dominant upper limb/ other side	2-choiceSM Non dominant upper limb/ same side	2-choiceSM Non dominant upper limb/ other side
Skewness	0.503	0.333	0.451	1.778
Std. Error of	0.491	0.491	0.491	0.491
z skewness	1.024	0.678	0.919	3.621
Kurtosis	-0.157	-0.859	-0.219	5.093
Std. Error of Kurtosis	0.953	0.953	0.953	0.953
z kurtosis	0.165	0.901	0.230	5.344

Table 39: Skewness and kurtosis for 2-choice speed of movement in the upper limb in healthy Participants

	2-choiceRT Dominant upper limb/ same side	2-choiceRT Dominant upper limb/ other side	2-choiceRT Non dominant upper limb/ same side	2-choiceRT Non dominant upper limb/ other side
Skewness	0.396	-.067	0.584	0.530
Std. Error of	0.661	0.661	0.661	0.661
z skewness	0.599	0.101	0.884	0.802
Kurtosis	-0.808	-0.563	-1.077	0.819
Std. Error of Kurtosis	1.279	1.279	1.279	1.279
z kurtosis	0.632	0.440	0.842	0.640

Table 40: Skewness and kurtosis for 2-choice response time in the upper limb in healthy participants.

	2-choiceSM Dominant upper limb/ same side	2-choiceSM Dominant upper limb/ other side	2-choiceSM Non dominant upper limb/ same side	2-choiceSM Non dominant upper limb/ other side
Skewness	1.084	1.374	0.951	1.236
Std. Error of	0.661	0.661	0.661	0.661
z skewness	1.640	2.079	1.439	1.870
Kurtosis	0.976	0.871	1.347	2.470
Std. Error of Kurtosis	1.279	1.279	1.279	1.279
z kurtosis	0.763	0.681	1.053	1.930

Table 41: Skewness and kurtosis for 2-choice speed of movement in the upper limb in patients with Tennis elbow.

2.6.1.3 The Kolmogorov-smirnov test

The following variables were significantly non normal in the healthy participants group, the 2-choice RT of the dominant upper limb/ same side $D(22) = 0.2$, the 2-choice SM of the dominant upper limb/ same side $D(22) = 0.191$, and the 2-choice RT of the dominant upper limb/ other side $D(22) = 0.249$. While in the patients with tennis elbow group, only the 2-choice SM of the affected upper limb/ other side $D(22) = 0.253$ was significantly non normal. (Table 42).

Tests of Normality Kolmogorov-Smirnov						
	Healthy			Patients		
	Statistic	df	Sig.	Statistic	df	Sig.
2-choiceRT Dominant/ Affected upper limb/ same side	.200	22	.022	.205	11	.200
2-choiceSM Dominant/ Affected upper limb/ same side	.191	22	.035	.198	11	.200
2-choiceRT Dominant/ Affected upper limb/ other side	.249	22	.001	.132	11	.200
2-choiceSM Dominant/ Affected upper limb/ other side	.112	22	.200	.253	11	.047
2-choiceRT Non dominant/ Non affected upper limb/ same side	.174	22	.081	.201	11	.200
2-choiceSM Non dominant/ Non affected upper limb/ same side	.137	22	.200	.158	11	.200
2-choiceRT Non dominant/ Non affected upper limb/ other side	.123	22	.200	.139	11	.200
2-choiceSM Non dominant/ Non affected upper limb/ other side	.172	22	.088	.182	11	.200

Table 42: Kolmogorov-Smirnov test of normality for 2-choice response time and speed of movement in the upper limb.

2.6.2 Homogeneity of variance

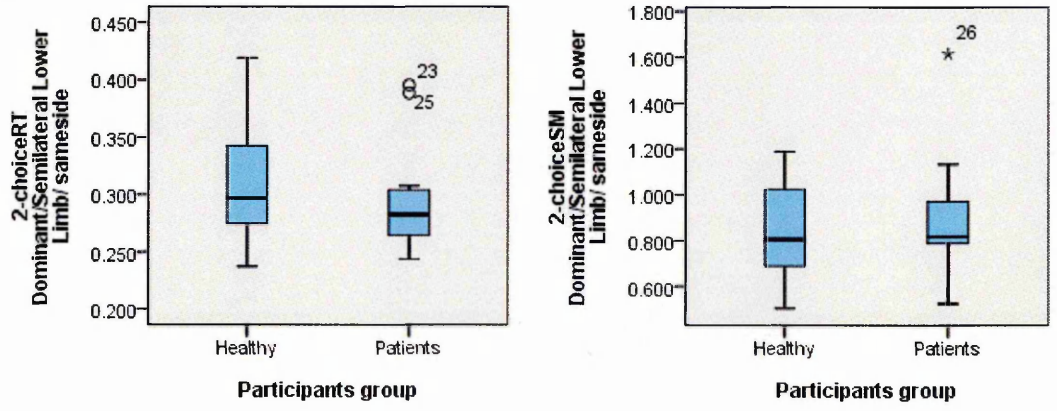
For the 2-choice upper limb, all the SM variances were significantly different in the two groups; the 2-choice SM dominant/affected upper limb/ same side, $F(1,31) = 4.931$, $P < 0.05$., the 2-choice SM dominant/affected upper limb/ other side, $F(1,31) = 9.803$, $p < 0.01$, the 2-choice SM non dominant/non affected upper limb/ same side, $F(1,31) = 10.383$, $p < 0$ .05 and the 2-choice SM non dominant/non affected upper limb/ other side, $F(1,31) = p < 0.05$. (Table 43).

Test of Homogeneity of Variance Based on Mean				
	Levene Statistic	df1	df2	Sig.
2-choiceRT Dominant/ Affected upper limb/ same side	2.046	1	31	.163
2-choiceSM Dominant/ Affected upper limb/ same side	4.931	1	31	.034
2-choiceRT Dominant/ Affected upper limb/ other side	1.173	1	31	.287
2-choiceSM Dominant/ Affected upper limb/ other side	9.803	1	31	.004
2-choiceRT Non dominant/ Non affected upper limb/ same side	.141	1	31	.710
2-choiceSM Non dominant/ Non affected upper limb/ same side	10.383	1	31	.003
2-choiceRT Non dominant/ Non affected upper limb/ other side	.403	1	31	.530
2-choiceSM Non dominant/ Non affected upper limb/ other side	4.738	1	31	.037

Table 43: Levene's test of homogeneity of variance for 2-choice response time and speed of movement in the upper limb.

2.7 Outliers in the 2-choice response time and speed of movement in the lower limb

Prior to perform any statistical analysis, the 2-choice RT and SM data were plotted using simple box plots so outliers could be identified (Figure 18). Four outliers were identified, one was in RT and three were in SM. The outlier of 2-choice RT of the contra-lateral lower limb/ other side will not be removed because it came from a patient and again similar to the debate earlier this patient is representative of the population of interest and the long time of response time could reflect the chronicity of the condition.



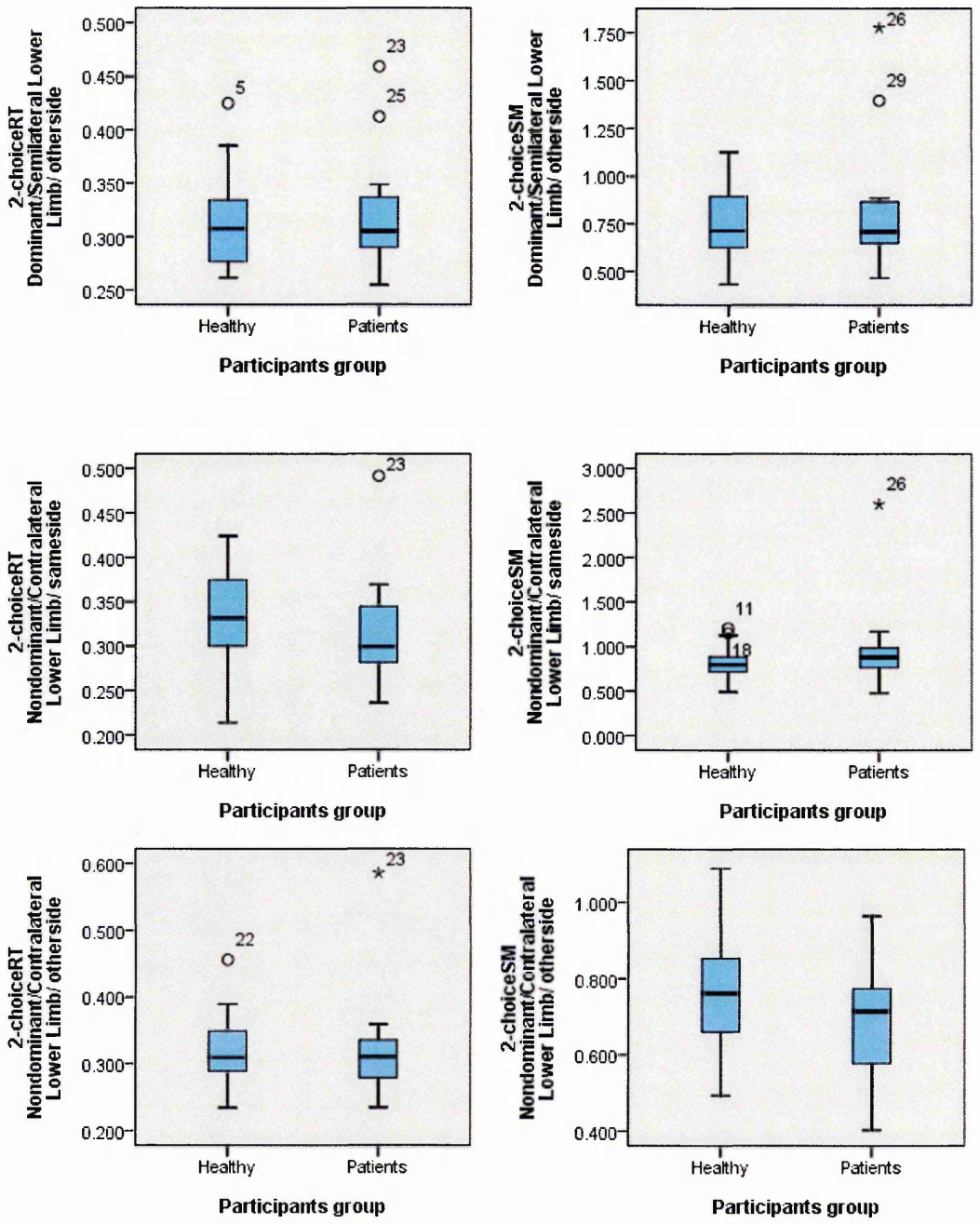


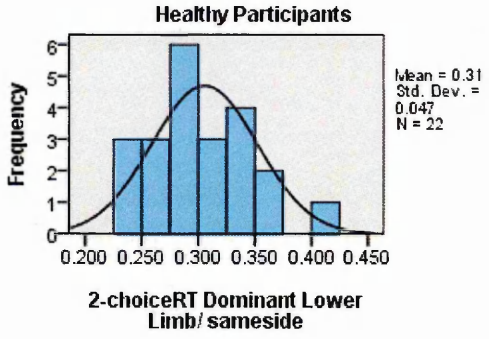
Figure 18: Box plots for 2-choice response time and speed of movement in the lower limb.

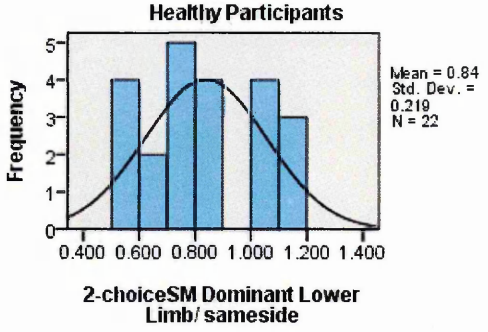
2.8 Checking the assumptions of the 2-choice response time and speed of movement in the lower limb

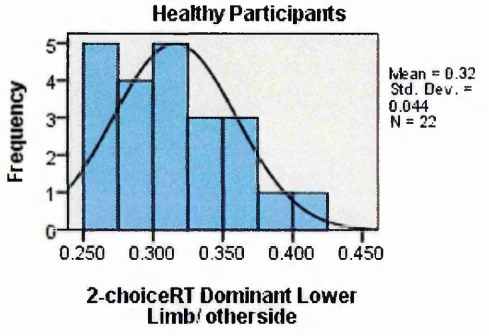
2.8.1 Normality

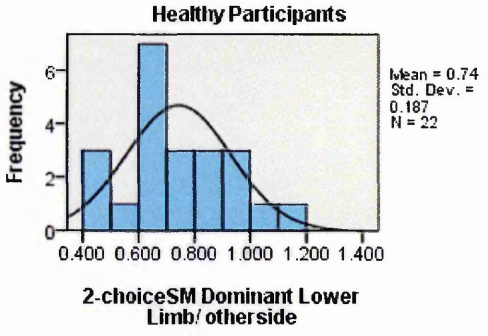
2.8.1.1 Histograms and Q-Q plots

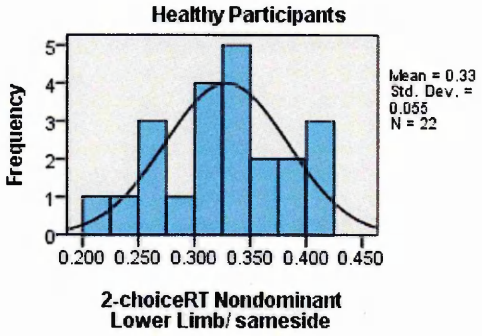
The 2-choice RT and SM data in the lower limb was plotted using Q-Q plots and histograms (Figure 19-20). The histograms were visually checked for skeweness and kurtosis. In healthy participants' positive skew could be seen in the 2-choice RT dominant lower limb/ other side while negative kurtosis or platykurtic could be seen in the 2-choice SM dominant lower limb/ other side and the 2-choice SM non dominant lower limb/ same side. In patients with tennis elbow, positive skew could be seen in the 2-choice RT semi-lateral lower limb/ other side and the 2-choice RT contra-lateral lower limb/ other side. While, negative kurtosis could be seen in the 2-choice SM semi-lateral lower limb/ same side, the 2-choice SM semi-lateral lower limb/ other side, 2-choice RT contra-lateral lower limb/ same side and the 2-choice SM contra-lateral lower limb/ same side.

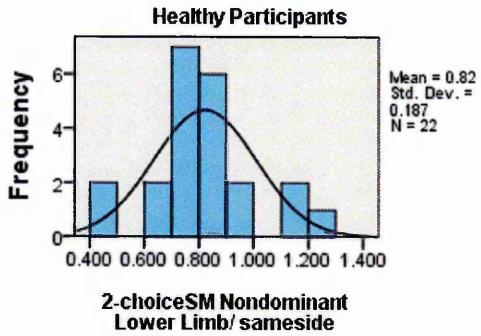


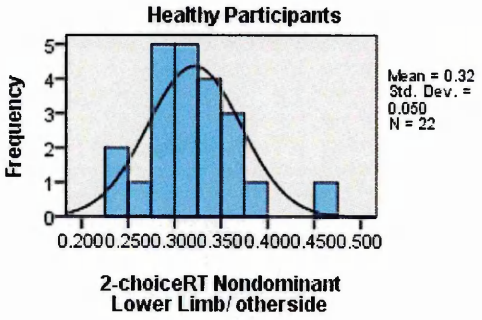


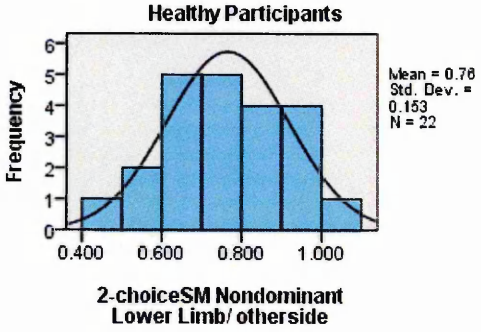


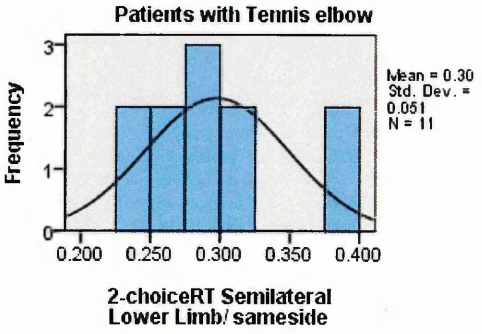


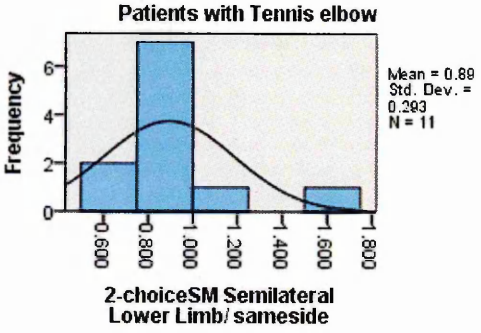

Healthy Participants
Frequency
Mean = 0.33
Std. Dev. = 0.055
N = 22
0.200 0.250 0.300 0.350 0.400 0.450
2-choiceRT Nondominant Lower Limb/ sameside

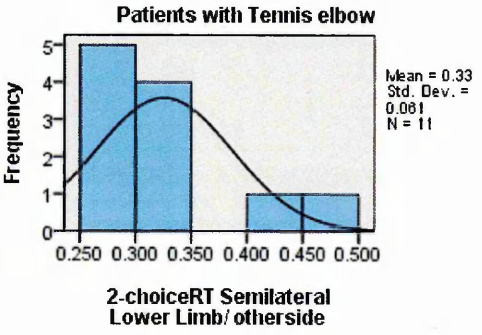

Healthy Participants
Frequency
Mean = 0.82
Std. Dev. = 0.187
N = 22
0.400 0.600 0.800 1.000 1.200 1.400
2-choiceSM Nondominant Lower Limb/ sameside

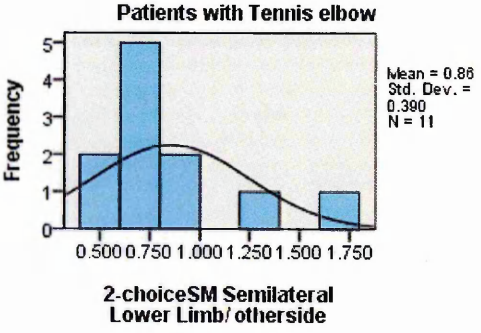

Healthy Participants
Frequency
Mean = 0.32
Std. Dev. = 0.050
N = 22
0.200 0.250 0.300 0.350 0.400 0.450 0.500
2-choiceRT Nondominant Lower Limb/ otherside


Healthy Participants
Frequency
Mean = 0.76
Std. Dev. = 0.153
N = 22
0.400 0.600 0.800 1.000
2-choiceSM Nondominant Lower Limb/ otherside


Patients with Tennis elbow
Frequency
Mean = 0.30
Std. Dev. = 0.051
N = 11
0.200 0.250 0.300 0.350 0.400
2-choiceRT Semilateral Lower Limb/ sameside


Patients with Tennis elbow
Frequency
Mean = 0.89
Std. Dev. = 0.293
N = 11
0.600 0.800 1.000 1.200 1.400 1.600 1.800
2-choiceSM Semilateral Lower Limb/ sameside


Patients with Tennis elbow
Frequency
Mean = 0.33
Std. Dev. = 0.061
N = 11
0.250 0.300 0.350 0.400 0.450 0.500
2-choiceRT Semilateral Lower Limb/ otherside


Patients with Tennis elbow
Frequency
Mean = 0.86
Std. Dev. = 0.390
N = 11
0.500 0.750 1.000 1.250 1.500 1.750
2-choiceSM Semilateral Lower Limb/ otherside

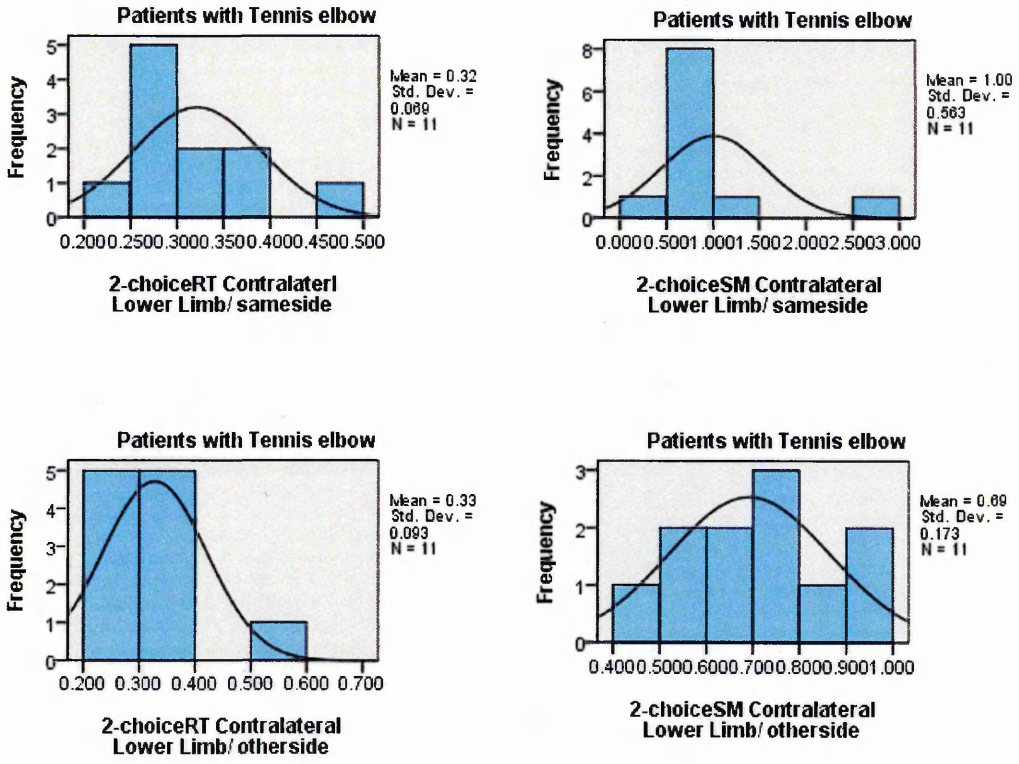
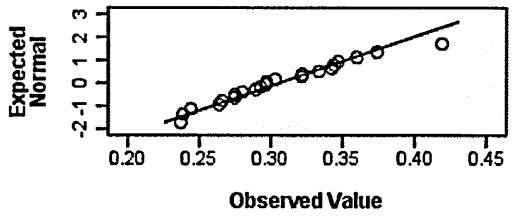
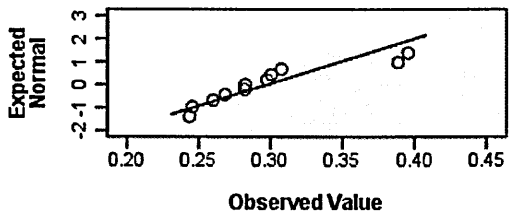


Figure 19: Histograms for 2-choice response time and speed of movement in healthy participants and patients with Tennis elbow.

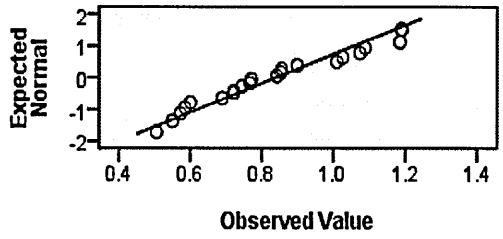
Normal Q-Q Plot of 2-choiceRT Dominant Lower Limb/ sameside (Healthy participants)



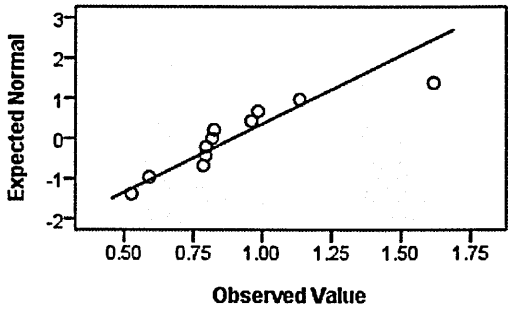
Normal Q-Q Plot of 2-choiceRT Semilateral Lower Limb/ sameside (Patients with Tennis elbow)



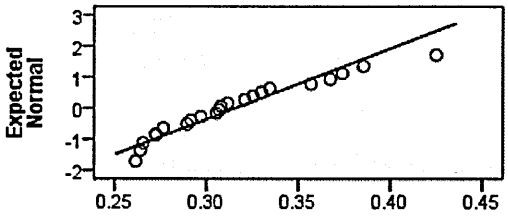
Normal Q-Q Plot of twochoiceSM Dominant Lower Limb/ sameside (Healthy participants)



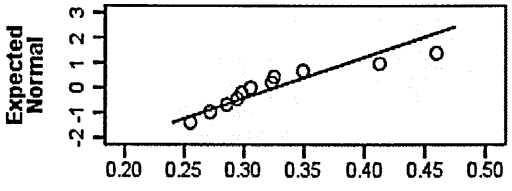
Normal Q-Q Plot of 2-choiceSM Semilateral Lower ...



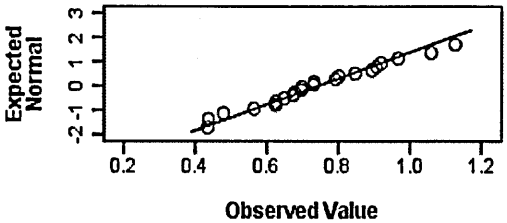
Normal Q-Q Plot of 2-choiceRT Dominant Lower Limb/ otherside (Healthy participants)



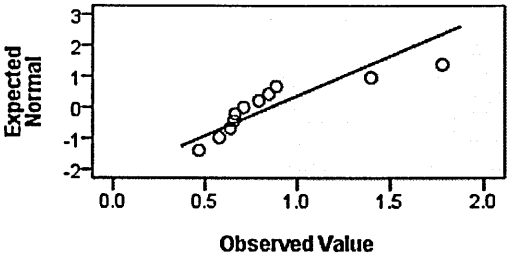
Normal Q-Q Plot of 2-choiceRT Semilateral Lower Limb/ otherside (Patients with Tennis elbow)



Normal Q-Q Plot of 2-choiceSM Dominant Lower Limb/ otherside (Healthy participants)



Normal Q-Q Plot of 2-choiceSM Semilateral Lower Limb/ otherside (Patients with Tennis elbow)



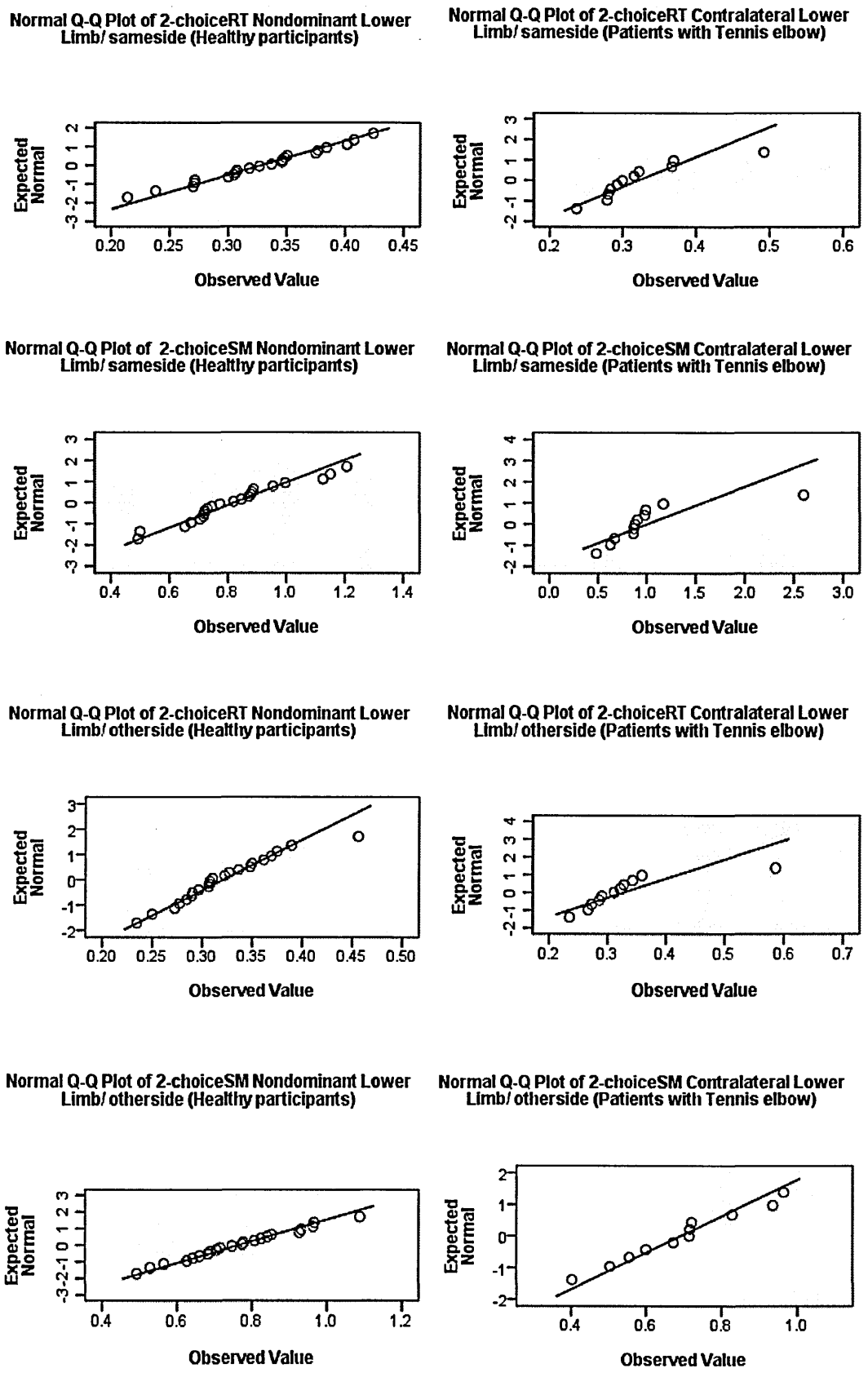


Figure 20: Q-Q plots for 2-choice response time and speed of movement in the lower limb.

2.8.1.2 Skewness and Kurtosis scores and their z-scores

	2-choiceRT Dominant lower limb/ sameside	2-choiceRT Dominant lower limb/ otherside	2-choiceRT Non dominant lower limb/ sameside	2-choiceRT Non dominant lower limb/ otherside
Skewness	.557	.860	-.218	.753
Std. Error of	.491	.491	.491	.491
z skewness	1.134	1.752	0.444	1.534
Kurtosis	.102	.281	-.406	1.162
Std. Error of Kurtosis	.953	.953	.953	.953
z kurtosis	0.11	0.295	0.426	1.219

Table 44: Skewness and kurtosis for 2-choice response time in the lower limb in healthy participants.

	2-choiceSM Dominant lower limb/ sameside	2-choiceSM Dominant lower limb/ otherside	2-choiceSM Non dominant lower limb/ sameside	2-choiceSM Non dominant lower limb/ otherside
Skewness	.259	.226	.387	.187
Std. Error of	.491	.491	.491	.491
z skewness	0.527	0.46	0.788	0.381
Kurtosis	-1.094	-.336	.037	-.387
Std. Error of Kurtosis	.953	.953	.953	.953
z kurtosis	1.15	0.353	0.0388	0.406

Table 45: Skewness and kurtosis for 2-choice speed of movement in the lower limb in healthy participants

	2-choiceRT Semi-lateral lower limb/ sameside	2-choiceRT Semi-lateral lower limb/ otherside	2-choiceRT Contra-lateral lower limb/ sameside	2-choiceRT Contra-lateral lower limb/ otherside
Skewness	1.195	1.301	1.626	2.427
Std. Error of	.661	.661	.661	.661
z skewness	1.808	1.968	2.46	3.671
Kurtosis	.592	1.239	3.404	6.984
Std. Error of Kurtosis	1.279	1.279	1.279	1.279
z kurtosis	0.463	0.969	2.661	5.461

Table 46: Skewness and kurtosis for 2-choice response time in the lower limb in patients with Tennis elbow

	2-choiceSM Semi-lateral lower limb/ sameside	2-choiceSM Semi-lateral lower limb/ otherside	2-choiceSM Contra-lateral lower limb/ sameside	2-choiceSM Contra-lateral lower limb/ otherside
Skewness	1.500	1.714	2.624	.067
Std. Error of	.661	.661	.661	.661
z skewness	2.269	2.593	3.969	0.101
Kurtosis	3.316	2.503	7.891	-.510
Std. Error of Kurtosis	1.279	1.279	1.279	1.279
z kurtosis	2.593	1.957	6.17	0.399

Table 47: Skewness and kurtosis for 2-choice speed of movement in the lower limb in patients with Tennis elbow

After ignoring the minus sign, values of z-scores greater than 1.96 are significant at $p<0.05$. z-scores that are significantly skewed or kurtosis are highlighted in grey (Table 44-47).

2.8.1.3 The Kolmogorov-Smirnov test

The 2-choice SM semi-lateral lower limb/ other side, $D(11) = 0.287$, $p <$ .0,the 2-choice SM contra-lateral lower limb/ same side, $D(11) = 0.326$, $p <0.01$ and the 2-choice RT contra-lateral lower limb/ other side, $D(11) = 0.274$, $p < 0.05$, were all significantly non normal. (Table 48).

Tests of Normality Kolmogorov-Smirnov						
	Healthy			Patients		
	Statistic	df	Sig.	Statistic	df	Sig.
2-choiceRT Dominant/ Semi-lateral lower limb/ same side	.118	22	.200	.240	11	.076
2-choiceSM Dominant/ Semi-lateral lower limb/ same side	.121	22	.200	.229	11	.109
2-choiceRT Dominant/ Semi-lateral lower limb/ other side	.128	22	.200	.230	11	.109
2-choiceSM Dominant/ Semi-lateral lower limb/ other side	.113	22	.200	.287	11	.012
2-choiceRT Non dominant/ Contra-lateral lower limb/ same side	.080	22	.200	.221	11	.138
2-choiceSM Non dominant/ Contra-lateral lower limb/ same side	.131	22	.200	.326	11	.002
2-choiceRT Non dominant/ Contra-lateral lower limb/ other side	.129	22	.200	.274	11	.020
2-choiceSM Non dominant/ Contra-lateral lower limb/ other side	.084	22	.200	.162	11	.200

Table 48: Kolmogorov-Smirnov test of normality for 2-choice RT and SM in the lower limb including outliers.

2.8.2 Homogeneity of variance

For the 2-choice RT and SM in the lower limb, all the variances were equal, so the homogeneity of variance was not violated. (Table 49).

Test of Homogeneity of Variance Based on Mean				
	Levene Statistic	df1	df2	Sig.
2-choiceRT Dominant/ Semi-lateral lower limb/ same side	.006	1	31	.940
2-choiceSM Dominant/ Semi-lateral lower limb/ same side	.172	1	31	.681
2-choiceRT Dominant/ Semi-lateral lower limb/ other side	.752	1	31	.393
2-choiceSM Dominant/ Semi-lateral lower limb/ other side	3.599	1	31	.067
2-choiceRT Non dominant/ Contra-lateral lower limb/ same side	.091	1	31	.765
2-choiceSM Non dominant/ Contra-lateral lower limb/ same side	3.030	1	31	.092
2-choiceRT Non dominant/ Contra-lateral lower limb/ other side	.936	1	31	.341
2-choiceSM Non dominant/ Contra-lateral lower limb/ other side	.073	1	31	.788

Table 49: Levene's test of homogeneity of variance for 2-choice RT and SM in the lower limb including outliers.

2.9 Normality and homogeneity of variance of response time and speed of movement after excluding missing data

2.9.1 1-choice RT-SM UP.L

The 1-choice RT non dominant upper limb, $D(22) = 0.194$, $p < 0.05$ and the 1-choice SM non dominant upper limb, $D(22) = 0.223$, $p < 0.01$ were both significantly non normal. (Table 50).

The variances were significantly different in the 1-choice RT non dominant/ non affected upper limb, $F(1,31) = 4.176$, $p < 0.05$ and the 1-choice SM non dominant/ non affected upper limb, $F(1,31) = 10.469$, $p < 0.01$. (Table 51).

Test of Homogeneity of Variance Based on Mean				
	Levene Statistic	df1	df2	Sig.
1-choiceRT Dominant/ Affected Upper limb	.553	1	31	.463
1-choiceSM Dominant/ Affected Upper limb	1.840	1	30	.185
1-choiceRT Non dominant/ Non affected Upper limb	4.176	1	31	.050
1-choiceSM Non dominant/ Non affected Upper limb	10.469	1	31	.003

Table 50: Levene's test of homogeneity of variance for 1-choice RT and SM in the upper limb excluding outliers

	Kolmogorov-Smirnov					
	Healthy			Patients		
	Statistic	df	Sig.	Statistic	df	Sig.
2-choiceRT Dominant/ Affected Upper limb/ same side	.200	22	.022	.205	11	.200
2-choiceSM Dominant/ Affected Upper limb/ same side	.191	22	.035	.198	11	.200
2-choiceRT Dominant/ Affected Upper limb/ other side	.249	22	.001	.132	11	.200
2-choiceSM Dominant/ Affected Upper limb/ other side	.112	22	.200	.253	11	.047
2-choiceRT Non dominant/ Non affected Upper limb/ same side	.174	22	.081	.201	11	.200
2-choiceSM Non dominant/ Non affected Upper limb/ same side	.137	22	.200	.158	11	.200
2-choiceRT Non dominant/ Non affected Upper limb/ other side	.123	22	.200	.139	11	.200
2-choiceSM Non dominant/ Non affected Upper limb/ other side	.076	21	.200	.182	11	.200

Table 51: Kolmogorov-Smirnov test of normality for 2-choice RT and SM in the upper limb excluding outliers

2.9.2 2-choice RT-SM UP.L

The following variables were significantly non normal; the 2-choice RT dominant upper limb/ same side, $D(22) = 0.2$, $p < 0.05$, the 2-choice SM dominant upper limb/ same side, $D(22) = 0.191$, $p < 0.05$, the 2-choice RT dominant upper limb/ other side, $D(22) = 0.249$, $p < 0.001$ and the 2-choice SM affected upper limb/ other side, $D(11) = 0.253$, $p < 0.05$. (Table 52).

The variances were significantly different for the following variables; the 2-choice dominant/ affected upper limb/ same side, $F(1,31) = 4.931$, $p < 0.05$, the 2-choice SM dominant/ affected upper limb/ other side, $F(1,31) = 9.803$, $p < 0.01$, the 2-choice SM non dominant/ non affected upper limb/ same side, $F(1,31) = 10.383$, $p < 0.01$, the 2-choice non dominant/ non affected upper limb/ other side, $F(1,31) = 8.385$, $p < 0.01$. (Table 53).

	Kolmogorov-Smirnov					
	Healthy			Patients		
	Statistic	df	Sig.	Statistic	df	Sig.
1-choiceRT Dominant/ Affected Upper limb	.096	22	.200	.170	11	.200
1-choiceSM_Dominant/ Affected Upper limb	.153	22	.197	.207	10	.200
1-choiceRT Non dominant/ Non affected Upper limb	.194	22	.030	.181	11	.200
1-choiceSM Non dominant/ Non affected Upper limb	.223	22	.006	.188	11	.200

Table 52: Kolmogorov-Smirnov test of normality for 1-choice RT and SM in the upper limb excluding outliers

Test of Homogeneity of Variance Based on Mean				
	Levene Statistic	df1	df2	Sig.
2-choiceRT Dominant/ Affected Upper limb/ same side	2.046	1	31	.163
2-choiceSM Dominant/ Affected Upper limb/ same side	4.931	1	31	.034
2-choiceRT Dominant/ Affected Upper limb/ other side	1.173	1	31	.287
2-choiceSM Dominant/ Affected Upper limb/ other side	9.803	1	31	.004
2-choiceRT Non dominant/ Nonffected Upper limb/ same side	.141	1	31	.710
2-choiceSM Non dominant/ Nonffected Upper limb/ same side	10.383	1	31	.003
2-choiceRT Non dominant/ Nonffected Upper limb/ other side	.403	1	31	.530
2-choiceSM_ Non dominant/ Nonffected Upper limb/ other side	8.385	1	30	.007

Table 53: Levene's test of homogeneity of variance for 2-choice RT and SM in the upper limb excluding outliers.

2.9.3 2-choice RT-SM L.L

Only the 2-choice RT contra-lateral lower limb $D(11) = 0.274, p < 0.05$. was significanthly non normal. (Table 54). Homogeneity of variance was not violated in the 2-choice RT and SM lower limb as all the variances were equal. (Table 55).

	Kolmogorov-Smirnov					
	Healthy			Patients		
	Statistic	df	Sig.	Statistic	df	Sig.
2-choiceRT Dominant/ Semi-lateral lower limb/ same side	.118	22	.200	.240	11	.076
2-choiceSM Dominant/ Semi-lateral lower limb/ same side	.121	22	.200	.221	10	.180
2-choiceRT Dominant/ Semi-lateral lower limb/ other side	.128	22	.200	.230	11	.109
2-choiceSM Dominant/ Semi-lateral lower limb/ other side	.113	22	.200	.215	10	.200
2-choiceRT Non dominant/ Contra-lateral lower limb/ same side	.080	22	.200	.221	11	.138
2-choiceSM Non dominant/ Contra-lateral lower limb/ same side	.131	22	.200	.240	10	.106
2-choiceRT Non dominant/ Contra-lateral lower limb/ other side	.129	22	.200	.274	11	.020
2-choiceSM Non dominant/ Contra-lateral lower limb/ other side	.084	22	.200	.162	11	.200

Table 54: Kolmogorov-Smirnov test of normality for 2-choice RT and SM in the lower limb excluding outliers

Test of Homogeneity of Variance Based on Mean				
	Levene Statistic	df1	df2	Sig.
2-choiceRT Dominant/ Semi-lateral lower limb/ same side	.006	1	31	.940
2-choiceSM Dominant/ Semi-lateral lower limb/same side	1.610	1	30	.214
2-choiceRT Dominant/ Semi-lateral lower limb/other side	.752	1	31	.393
2-choiceSM Dominant/ Semi-lateral lower limb/other side	.247	1	30	.623
2-choiceRT Non dominant/ Contra-lateral lower limb/ same side	.091	1	31	.765
2-choiceSM Non dominant/ Contra-lateral lower limb/ same side	.021	1	30	.887
2-choiceRT Non dominant/ Contra-lateral lower limb/ other side	.936	1	31	.341
2-choiceSM Non dominant/ Contra-lateral lower limb/ other side	.073	1	31	.788

Table 55: Levene's test of homogeneity of variance for 2-choice RT and SM in the lower limb excluding outliers.

2.10Normality and homogeneity of variance of response time and speed of movement after transformation, (excluding missing data).

2.10.11-choice RT-SM UP.L

2.10.1.1 Log transformation

The log1-choice RT non dominant upper limb, $D(22) = 0.199$, $p < 0.05$ and the log1-choice SM non dominant upper limb $D(22) = .207$, $p < .05$ were both significantly non normal. (Table 56). The variances were significantly different only in the log1-choice SM non dominant/ non affected upper limb, $F(1,31) = 6.497$, $p < 0.05$. (Table 57).

	Kolmogorov-Smirnov					
	Healthy			Patients		
	Statistic	df	Sig.	Statistic	df	Sig.
log1-choiceRT Dominant/ affected upper limb	.093	22	.200	.174	11	.200
log1-choiceSM Dominant/ affected upper limb	.137	22	.200	.166	10	.200
log1-choiceRT Non dominant/ non affected upper limb	.199	22	.023	.176	11	.200
log1-choiceSM Non dominant/ non affected upper limb	.207	22	.015	.151	11	.200

Table 56: Kolmogorov-Smirnov test of normality for 1-choice RT and SM in the upper limb after log transformation (excluding outliers).

Test of Homogeneity of Variance Based on Mean				
	Levene Statistic	df1	df2	Sig.
log1-choiceRT Dominant/ affected upper limb	.469	1	31	.498
log1-choiceSM Dominant/ affected upper limb	1.592	1	30	.217
log1-choiceRT Non dominant/ non affected upper limb	3.313	1	31	.078
log1-choiceSM Non dominant/ non affected upper limb	6.497	1	31	.016

Table 57: Levene's test of homogeneity of variance for 1-choice RT and SM in the upper limb after log transformation (excluding outliers)

2.10.1.2 Square root transformation

The square root of the 1-choice RT non dominant upper limb, $D(22) = 0.206$, $p < 0.05$ and the square root of the 1-choice SM non dominant upper limb, $D(22) = .204$, $p < 0.05$ were both significantly non normal. (Table 58). The variances were significantly different in the square root of the 1-choice SM non dominant/ non affected upper limb, $F(1,31) = 8.612$, $p < 0.01$. (Table 59).

	Kolmogorov-Smirnov					
	Healthy			Patients		
	Statistic	df	Sig.	Statistic	df	Sig.
sqrt1-choiceRT Dominant/ affected upper limb	.089	22	.200	.179	11	.200
sqrt1-choiceSM Dominant/ affected upper limb	.135	22	.200	.167	10	.200
sqrt1-choiceRT Non dominant/ non affected upper limb	.206	22	.016	.170	11	.200
sqrt1-choiceSM Non dominant/ non affected upper limb	.204	22	.018	.157	11	.200

Table 58: Kolmogorov-Smirnov test of normality for 1-choice RT and SM in the upper limb after square root transformation (excluding outliers).

Test of Homogeneity of Variance Based on Mean				
	Levene Statistic	df1	df2	Sig.
sqrt1-choiceRT Dominant/ affected upper limb	.498	1	31	.485
sqrt1-choiceSM Dominant/ affected upper limb	1.591	1	30	.217
sqrt1-choiceRT Non dominant/ non affected upper limb	3.603	1	31	.067
sqrt1-choiceSM Non dominant/ non affected upper limb	8.612	1	31	.006

Table 59: Levene's test of homogeneity of variance for 1-choice RT and SM in the upper limb after square root transformation (excluding outliers).

2.10.1.3 Reciprocal transformation

The following variables were significantly non normal; the reciprocal of 1-choice RT non dominant upper limb $D(22) = 0.241$, $p < 0.01$, the reciprocal of the 1-choice SM non dominant upper limb, $D(22) = 0.227$, $p < 0.01$ and the reciprocal of the 1-choice SM non affected upper limb, $D(11) = 0.304$, $p < 0.01$. (Table 60). The variances were significantly different in the reciprocal of 1-choice RT non dominant/ non affected upper limb, $F(1,31) = 4.176$, $p < 0.05$ and the reciprocal of 1-choice non dominant/ non affected upper limb, $F(1,31) = 10.469$, $p < 0.01$. (Table 61).

	Kolmogorov-Smirnov					
	Healthy			Patients		
	Statistic	df	Sig.	Statistic	df	Sig.
rec1-choiceRT Dominant/ affected upper limb	.091	22	.200	.203	11	.200
rec1-choiceSM Dominant/ affected upper limb	.080	22	.200	.163	10	.200
rec1-choiceRT Non dominant/ non affected upper limb	.241	22	.002	.141	11	.200
rec1-choiceSM Non dominant/ non affected upper limb	.227	22	.004	.304	11	.005

Table 60: Kolmogorov-Smirnov test of normality for 1-choice RT and SM in the upper limb after reciprocal transformation (excluding outliers).

Test of Homogeneity of Variance Based on Mean				
	Levene Statistic	df1	df2	Sig.
rec1-choiceRT Dominant/ affected upper limb	.553	1	31	.463
rec1-choiceSM Dominant/ affected upper limb/	1.840	1	30	.185
rec1-choiceRT Non dominant/ non affected upper limb	4.176	1	31	.050
rec1-choiceSM Non dominant/ non affected upper limb	10.469	1	31	.003

Table 61: Levene's test of homogeneity of variance for 1-choice RT and SM in the upper limb after reciprocal transformation (excluding outliers).

2.10.21-choice RT-SM L.L

2.10.2.1 Log transformation

The kolmogorov-Smirnov test was not significant for the log 1-choice RT and SM in the lower limb. (Table 62). The variances were significantly different in the log1-choice non dominant/ contra-lateral lower limb, $F(1,31) = 7.503$, $p < .01$. (Table 63).

	Kolmogorov-Smirnov					
	Healthy			Patients		
	Statistic	df	Sig.	Statistic	df	Sig.
log1-choiceRT Dominant/ Semi-lateral lower limb	.171	22	.095	.182	11	.200
log1-choiceSM Dominant/ Semi-lateral lower limb	.110	22	.200	.169	11	.200
log1-choiceRT Non dominant/ Contra-lateral lower limb	.114	22	.200	.324	11	.002
log1-choiceSM Non dominant/ Contra-lateral lower limb	.081	22	.200	.174	11	.200

Table 62: Kolmogorov-Smirnov test of normality for 1-choice RT and SM in the lower limb after log transformation

Test of Homogeneity of Variance Based on Mean				
	Levene Statistic	df1	df2	Sig.
log1choiceRT Dominant Semi-lateral lower limb	.045	1	31	.833
log1choiceSM Dominant Semi-lateral lower limb	.674	1	31	.418
log1choiceRT Non dominant Contra-lateral lower limb	.238	1	31	.629
log1choiceSM Non dominant Contra-lateral lower limb	7.506	1	31	.010

Table 63: Levene's test of homogeneity of variance for 1-choice RT and SM in the lower limb after log transformation

2.10.2.2 Square root transformation

The square root of the 1-choice RT contra-lateral lower limb, D(11) = 0.312, $p < 0.01$ was significantly non normal. (Table 64). The variances were significantly different in the square root of the 1-choice SM non dominant/ contra-lateral lower limb, $F(1,31) = 5.874, p < 0.05$. (Table 65).

	Kolmogorov-Smirnov					
	Healthy			Patients		
	Statistic	df	Sig.	Statistic	df	Sig.
sqrt1choiceRT Dominant Semi-lateral lower limb	.162	22	.135	.174	11	.200
sqrt1choiceSM Dominant Semi-lateral lower limb	.109	22	.200	.166	11	.200
sqrt1choiceRT Non dominant Contra-lateral lower limb	.119	22	.200	.312	11	.004
sqrt1choiceSM Non dominant Contra-lateral lower limb	.080	22	.200	.176	11	.200

Table 64: Kolmogorov-Smirnov test of normality for 1-choice RT and SM in the lower limb after square root transformation

Test of Homogeneity of Variance Based on Mean				
	Levene Statistic	df1	df2	Sig.
sqrt1choiceRT Dominant Semi-lateral lower limb	.045	1	31	.833
sqrt1choiceSM Dominant Semi-lateral lower limb	.604	1	31	.443
sqrt1choiceRT Non dominant Contra-lateral lower limb	.386	1	31	.539
sqrt1choiceSM Non dominant Contra-lateral lower limb	5.874	1	31	.021

Table 65: Levene's test of homogeneity of variance for 1-choice RT and SM in the lower limb after square root transformation

2.10.2.3 Reciprocal transformation

Kolmogorove-Smirnov test was not significant for the reciprocal of the 1-choice RT and SM in the lower limb. (Table 66). The variances were significantly different in the reciprocal of the 1-choice SM dominant/ semi-lateral lower limb, $F(1,31) = 4.582, p < 0.05$. (Table 67).

	Kolmogorov-Smirnov					
	Healthy			Patients		
	Statistic	df	Sig.	Statistic	df	Sig.
rec1choiceRT Dominant Semilalateral lower limb	.121	22	.200	.134	11	.200
rec1choiceRT Non dominant Contra-lateral lower limb	.155	22	.183	.218	11	.151
rec1choiceSMNon dominantContra-laterallowerlim	.143	22	.200	.247	11	.060
rec1choiceSM Dominant Semi-lateral lower limb	.125	22	.200	.211	11	.185

Table 66: Kolmogorov-Smirnov test of normality for 1-choice RT and SM in the lower limb after reciprocal transformation

Test of Homogeneity of Variance Based on Mean				
	Levene Statistic	df1	df2	Sig.
rec1choiceRT Dominant Semilalateral lower limb	.045	1	31	.832
rec1choiceRT Non dominant Contra-lateral lower limb	.637	1	31	.431
rec1choiceSM Non dominant Contra-lateral lower limb	.798	1	31	.378
rec1choiceSM Dominant Semi-lateral lower limb	4.582	1	31	.040

Table 67: Levene's test of homogeneity of variance for 1-choice RT and SM in the lower limb after reciprocal transformation

2.10.32-choice RT-SM UP.L

2.10.3.1 Log transformation

The log2-choice dominant/ affected upper limb/ other side, $D(22) = 0.241$, $p < .01$ was significantly non normal. (Table 68). The variances were significantly different in the log2-choice SM non dominant/ non affected upper limb/ same side, $F(1,31) = 9.561, p < 0.01$ and the log2-choice SM non dominant/ non affected upper limb/ other side, $F(1,31) = 5.672, p < 0.05$. (Table 69).

	Kolmogorov-Smirnov					
	Healthy			Patients		
	Statistic	df	Sig.	Statistic	df	Sig.
log2-choiceRT Dominant/ affected upper limb/same side	.196	22	.028	.204	11	.200
log2-choiceSM Dominant/ affected upper limb/same side	.167	22	.114	.163	11	.200
log2-choiceRT Dominant/ affected upper limb/other side	.241	22	.002	.131	11	.200
log2-choiceSM Dominant/ affected upper limb/other side	.105	22	.200	.223	11	.132
log2-choiceRT Non dominant/ non affected upper limb/same side	.169	22	.103	.197	11	.200
log2-choiceSM Non dominant/ non affected upper limb/same side	.120	22	.200	.146	11	.200
log2-choiceRT Non dominant/ non affected upper limb/other side	.117	22	.200	.132	11	.200
log2-choiceSM Non dominant/ non affected upper limb/other side	.078	21	.200	.152	11	.200

Table 68: Kolmogorov-Smirnov test of normality for 2-choice RT and SM in the upper limb after logt transformation (excluding outliers).

Test of Homogeneity of Variance Based on Mean				
	Levene Statistic	df1	df2	Sig.
log2-choiceRT Dominant/ affected upper limb/same side	3.599	1	31	.067
log2-choiceSM Dominant/ affected upper limb/same side	1.248	1	31	.272
log2-choiceRT Dominant/ affected upper limb/other side	.378	1	31	.543
log2-choiceSM Dominant/ affected upper limb/other side	1.422	1	31	.242
log2-choiceRT Non dominant/ non affected upper limb/same side	.216	1	31	.645
log2-choiceSM Non dominant/ non affected upper limb/same side	9.651	1	31	.004
log2-choiceRT Non dominant/ non affected upper limb/other side	1.246	1	31	.273
log2-choiceSM Non dominant/ non affected upper limb/other side	5.672	1	30	.024

Table 69: Levene's test of homogeneity of variance for 2-choice RT and SM in the upper limb after log transformation (excluding outliers)

2.10.3.2 Square root transformation

The square root of the 2-choice RT dominant upper limb/ same side, $D(22) = .191$, $p < 0.05$ and the square root of the 2-choice RT dominant/ affected upper limb/ other side, $D(22) = 0.234$, $p < 0.01$ were both significantky non normal. (Table 70).

The variances were significantly different in the square root of the 2-choice SM non dominant/ non affected upper limb/ same side, $F(1,31) = 10.722$, $p < 0.01$ and the square root of the 2-choice SM non dominant/ non affected upper limb/ other side, $F(1,31) = 7.228$, $p < 0.05$. (Table 71).

	Kolmogorov-Smirnov					
	Healthy			Patients		
	Statistic	df	Sig.	Statistic	df	Sig.
sqrt2-choiceRT Dominant/ affected upper limb/same side	.191	22	.035	.201	11	.200
sqrt2-choiceSM Dominant/ affected upper limb/same side	.165	22	.123	.165	11	.200
sqrt2-choiceRT Dominant/ affected upper limb/other side	.234	22	.003	.129	11	.200
sqrt2-choiceSM Dominant/ affected upper limb/other side	.103	22	.200	.223	11	.131
sqrt2-choiceRT Non dominant/ non affected upper limb/ same side	.162	22	.137	.192	11	.200
sqrt2-choiceSM Non dominant/ non affected upper limb/ same side	.117	22	.200	.145	11	.200
sqrt2-choiceRT Non dominant/ non affected upper limb/ other side	.111	22	.200	.125	11	.200
sqrt2-choiceSM Non dominant/ non affected upper limb/ other side	.083	21	.200	.154	11	.200

Table 70: Kolmogorov-Smirnov test of normality for 2-choice RT and SM in the upper limb after square root transformation (excluding outliers).

Test of Homogeneity of Variance Based on Mean				
	Levene Statistic	df1	df2	Sig.
sqrt2-choiceRT Dominant/ affected upper limb/same side	3.065	1	31	.090
sqrt2-choiceSM Dominant/ affected upper limb/same side	2.234	1	31	.145
sqrt2-choiceRT Dominant/ affected upper limb/other side	.589	1	31	.449
sqrt2-choiceSM Dominant/ affected upper limb/other side	3.914	1	31	.057
sqrt2-choiceRT Non dominant/ non affected upper limb/ same side	.198	1	31	.659
sqrt2-choiceSM Non dominant/ non affected upper limb/ same side	10.722	1	31	.003
sqrt2-choiceRT Non dominant/ non affected upper limb/ other side	.923	1	31	.344
sqrt2-choiceSM Non dominant/ non affected upper limb/ other side	7.228	1	30	.012

Table 71: Levene's test of homogeneity of variance for 2-choice RT and SM in the upper limb after square root transformation (excluding outliers)

2.10.3.3 Reciprocal transformation

The reciprocal of the 2-choice SM dominant upper limb/ same side, $D(22) = 0.207$, $p < 0.05$ was significantly non normal. (Table 72). The variances were significantly different in the following variables; the reciprocal of the 2-choice dominant/ affected upper limb/ same side, $F(1,31) = 4.931$, $p < 0.05$, the reciprocal of the 2-choice SM dominant/ affected upper limb/ other side, $F(1,31) = 9.803$, $p < 0.01$, the reciprocal of the 2-choice SM non dominant/ non affected upper limb/ other same side, $F(1,31) = 10.383$, $p < 0.01$ and the reciprocal of the 2-choice SM non dominant/ non affected upper limb/ other side, $F(1,31) = 8.385$, $p < 0.01$. (Table 73).

	Kolmogorov-Smirnov					
	Healthy			Patients		
	Statistic	df	Sig.	Statistic	df	Sig.
rec2-choiceRT Dominant/ affected upper limb/same side	.161	22	.144	.183	11	.200
rec2-choiceSM Dominant/ affected upper limb/same side	.207	22	.015	.167	11	.200
rec2-choiceRT Dominant/ affected upper limb/other side	.184	22	.051	.165	11	.200
rec2-choiceSM Dominant/ affected upper limb/other side	.122	22	.200	.128	11	.200
rec2-choiceRT Non dominant/ non affected upper limb/ same side	.125	22	.200	.162	11	.200
rec2-choiceSM Non dominant/ non affected upper limb/ same side	.152	22	.200	.234	11	.094
rec2-choiceRT Non dominant/ non affected upper limb/ other side	.084	22	.200	.167	11	.200
rec2-choiceSM Non dominant/ non affected upper limb/ other side	.142	21	.200	.181	11	.200

Table 72: Kolmogorov-Smirnov test of normality for 2-choice RT and SM in the upper limb after reciprocal transformation (excluding outliers).

Test of Homogeneity of Variance Based on Mean				
	Levene Statistic	df1	df2	Sig.
rec2-choiceRT Dominant/ affected upper limb/ same side	2.046	1	31	.163
rec2-choiceSM Dominant/ affected upper limb/same	4.931	1	31	.034
rec2-choiceRT Dominant/ affected upper limb/other side	1.173	1	31	.287
rec2-choiceSM Dominant/ affected upper limb/other side	9.803	1	31	.004
rec2-choiceRT Non dominant/ non affected upper limb/ same side	.141	1	31	.710
rec2choiceSM Non dominant/ non affected upper limb/ same side	10.383	1	31	.003
rec2-choiceRT Non dominant/ non affected upper limb/ other side	.403	1	31	.530
rec2-choiceSM Non dominant/ non affected upper limb/ other side	8.385	1	30	.007

Table 73: Levene's test of homogeneity of variance for 2-choice RT and SM in the upper limb after reciprocal transformation (excluding outliers).

2.10.42-choice RT-SM L.L

2.10.4.1 Log transformation

The log 2-choice RT contra-lateral lower limb/ other side, $D(11) = 0.256$, $p < 0.05$ was significantly non normal. (Table 74). The variances were equal for the log 2-choice RT and SM of the lower limb. (Table 75).

	Kolmogorov-Smirnov					
	Healthy			Patients		
	Statistic	df	Sig.	Statistic	df	Sig.
log2-choiceRT Dominant/ Semi-lateral lower limb/same side	.112	22	.200	.232	11	.100
log2-choiceSM Dominant/ Semi-lateral lower limb/same side	.109	22	.200	.239	10	.111
log-2choiceRT Dominant/ Semi-lateral lower limb/other side	.122	22	.200	.221	11	.138
log2-choiceSM Dominant/ Semi-lateral lower limb/other side	.093	22	.200	.185	10	.200
log2-choiceRT Non dominant/ Contra-lateral lower limb/ same side	.086	22	.200	.212	11	.180
log2-choiceSM Non dominant/ Contra-lateral lower limb/ same side	.114	22	.200	.259	10	.057
log2-choiceRT Non dominant/ Contra-lateral lower limb/other side	.123	22	.200	.256	11	.043
log2-choiceSM Non dominant/ Contra-lateral lower limb/other side	.083	22	.200	.145	11	.200

Table 74: Kolmogorov-Smirnov test of normality for 2-choice RT and SM in the lower limb after log transformation (excluding outliers)

Test of Homogeneity of Variance Based on Mean				
	Levene Statistic	df1	df2	Sig.
log2-choiceRT Dominant/ Semi-lateral lower limb/same side	.002	1	31	.964
log2-choiceSM Dominant/ Semi-lateral lower limb/same side	1.300	1	30	.263
log2-choiceRT Dominant/ Semi-lateral lower limb/other side	.497	1	31	.486
log2-choiceSM Dominant/ Semi-lateral lower limb/other side	.007	1	30	.934
log2-choiceRT Non dominant/ Contra-lateral lower limb/same side	.002	1	31	.965
log2-choiceSM Non dominant/ Contra-lateral lower limb/same side	.205	1	30	.654
log2-choiceRT Non dominant/ Contra-lateral lower limb/other side	.595	1	31	.446

log2-choiceSM Non dominant/ Contra-lateral lower limb/ other side	.751	1	31	.393

Table 75: Levene's test of homogeneity of variance for 2-choice RT and SM in the upper limb after log transformation (excluding outliers).

2.10.4.2 Square root transformation

The Kolmogorov-Smirnov test was not significant for the square root of the 2-choice RT and SM in the lower limb. (Table 76). The variances were equal for the square root of the 2-chocie RT and SM in the lower limb. (Table 77).

	Kolmogorov-Smirnov					
	Healthy			Patients		
	Statistic	df	Sig.	Statistic	df	Sig.
sqrt2-choiceRT Dominant/ Semi-lateral lower limb/same side	.105	22	.200	.223	11	.131
sqrt2-choiceSM Dominant/ Semi-lateral lower limb/same side	.108	22	.200	.242	10	.102
sqrt2-choiceRT Dominant/ Semi-lateral lower limb/other side	.116	22	.200	.213	11	.174
sqrt2-choiceSM Dominant/ Semi-lateral lower limb/other side	.096	22	.200	.184	10	.200
sqrt2-choiceRT Non dominant/ Contra-lateral lower limb/same side	.091	22	.200	.203	11	.200
sqrt2-choiceSM Non dominant/ Contra-lateral lower limb/same side	.113	22	.200	.261	10	.052
sqrt2-choiceRT Non dominant/ Contra-lateral lower limb/other side	.116	22	.200	.242	11	.071
sqrt2-choiceSM Non dominant/ Contra-lateral lower limb/other side	.082	22	.200	.141	11	.200

Table 76: Kolmogorov-Smirnov test of normality for 2-choice RT and SM in the lower limb after square root transformation (excluding outliers).

Test of Homogeneity of Variance Based on Mean				
	Levene Statistic	df1	df2	Sig.
sqrt2-choiceRT Dominant/ Semi-lateral lower limb/same side	.002	1	31	.961
sqrt2-choiceSM Dominant/ Semi-lateral lower limb/same side	1.451	1	30	.238
sqrt2-choiceRT Dominant/ Semi-lateral lower limb/other side	.552	1	31	.463
sqrt2-choiceSM Dominant/ Semi-lateral lower limb/other side	.061	1	30	.806
sqrt2-choiceRT Non dominant/ Contra-lateral lower limb/same side	.015	1	31	.904
sqrt2-choiceSM Non dominant/ Contra-lateral lower limb/same side	.115	1	30	.736
sqrt2-choiceRT Non dominant/ Contra-lateral lower limb/other side	.667	1	31	.420
sqrt2-choiceSM Non dominant/ Contra-lateral lower limb/other side	.399	1	31	.532

Table 77 : Levene's test of homogeneity of variance for 2-choice RT and SM in the lower limb after square root transformation (excluding outliers).

2.10.4.3 Reciprocal transformation

The reciprocal of the 2-choice SM semi-lateral lower limb/ same side, $D(11) = .304$, $p < 0$ .01and the reciprocal of the 2-choice SM contra-lateral lower limb/ same side, $D(11) = 0.312$, $p < 0.01$ were both significantly non normal. (Table 78). The variances were equal for the reciprocal 2-chocie RT and SM in the lower limb. (Table 79).

	Kolmogorov-Smirnov					
	Healthy			Patients		
	Statistic	df	Sig.	Statistic	df	Sig.
rec2-choiceRT Dominant/ Semi-lateral lower limb/same side	.090	22	.200	.176	11	.200
rec2-choiceSM Dominant/ Semi-lateral lower limb/same side	.116	22	.200	.304	10	.009
rec2-choiceRT Dominant/ Semi-lateral lower limb/other side	.099	22	.200	.163	11	.200
rec2-choiceSM Dominant/ Semi-lateral lower limb/other side	.158	22	.164	.146	10	.200
rec2-choiceRT Non dominant/ Contra-lateral lower limb/same side	.139	22	.200	.170	11	.200
rec2-choiceSM Non dominant/ Contra-lateral lower limb/same side	.148	22	.200	.312	10	.007
rec2-choiceRT Non dominant/ Contra-lateral lower limb/other side	.075	22	.200	.163	11	.200
rec2-choiceSM Non dominant/ Contra-lateral lower limb/other side	.097	22	.200	.183	11	.200

Table 78: Kolmogorov-Smirnov test of normality for 2-choice RT and SM in the lower limb after reciprocal transformation (excluding outliers).

Test of Homogeneity of Variance Based on Mean				
	Levene Statistic	df1	df2	Sig.
rec2-choiceRT Dominant/ Semi-lateral lower limb/same side	.006	1	31	.940
rec2-choiceSM Dominant/ Semi-lateral lower limb/same side	1.610	1	30	.214
rec2-choiceRT Dominant/ Semi-lateral lower limb/other side	.752	1	31	.393
rec2-choiceSM Dominant/ Semi-lateral lower limb/other side	.247	1	30	.623
rec2-choiceRT Non dominant/ Contra-lateral lower limb/same side	.091	1	31	.765
rec2-choiceSM Non dominant/ Contra-lateral lower limb/same side	.021	1	30	.887
rec2-choiceRT Non dominant/ Contra-lateral lower limb/other side	.936	1	31	.341
rec2-choiceSM Non dominant/ Contra-lateral lower limb/other side	.073	1	31	.788

Table 79: Levene's test of homogeneity of variance for 2-choice RT and SM in the lower limb after reciprocal transformation (excluding outliers).

2.11Mixed design ANOVA/ 1-choice response time

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Limb	3.520E-8	1	3.520E-8	.0004	.984
Limb * Tennis_elbow	9.952E-6	1	9.952E-6	.110	.742
Error(Limb)	.003	31	9.012E-5		
Dominance/Laterality	7.031E-6	1	7.031E-6	.109	.744
Dominance/Laterality * Tennis_elbow	5.611E-6	1	5.611E-6	.087	.770
Error(Dominance/Laterality)	.002	31	6.454E-5		
Limb * Dominance/Laterality	.000	1	.000	6.830	.014
Limb * Dominance/Laterality * Tennis_elbow	.000	1	.000	3.464	.072
Error(Limb*Dominance/Laterality)	.001	31	4.030E-5		

Table 80: Within subject effects for the 1-choice RT in the upper and lower limb

Tests of Between-Subjects Effects					
Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Tennis_elbow	2.675E-5	1	2.675E-5	.058	.812
Error	.014	31	.000		

Table 81: Between subjects effects for 1-choice RT in the upper and lower limb

2.12Mixed design ANOVA/ 2-choice response time

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Limb	3.250E-5	1	3.250E-5	.120	.731
Limb * Tennis_elbow	.001	1	.001	2.723	.109
Error(Limb)	.008	31	.000		
Dominance/Laterality	9.613E-5	1	9.613E-5	.595	.446
Dominance/Laterality * Tennis_elbow	7.016E-7	1	7.016E-7	.004	.948
Error(Dominance/Laterality)	.005	31	.000		
Target	.001	1	.001	5.643	.024
Target * Tennis_elbow	3.323E-6	1	3.323E-6	.028	.867
Error(Target)	.004	31	.000		
Limb * Dominance/Laterality	.001	1	.001	2.640	.114
Limb * Dominance/Laterality * Tennis_elbow	1.036E-5	1	1.036E-5	.052	.822
Limb * Target	1.078E-5	1	1.078E-5	.103	.750
Limb * Target * Tennis_elbow	.000	1	.000	2.680	.112
Error(Limb*Target)	.003	31	.000		
Dominance/Laterality * Target	7.387E-5	1	7.387E-5	.744	.395
Dominance/Laterality * Target * Tennis_elbow	9.485E-5	1	9.485E-5	.956	.336
Error(Dominance/Laterality*Target)	.003	31	9.925E-5		
Limb * Dominance/Laterality * Target	.000	1	.000	2.270	.142
Limb * Dominance/Laterality * Target * Tennis_elbow	3.752E-5	1	3.752E-5	.297	.590
Error(Limb*Dominance/Laterality*Target)	.004	31	.000		

Table 82: Within subject effects for the 2-choice RT in the upper and lower limb

Tests of Between-Subjects Effects					
Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Tennis_elbow	.001	1	.001	.586	.450
Error	.043	31	.001		

Table 83: Between subjects effects for 1-choice RT in the upper and lower limb.