

# **Submission for MD(res) Thesis**

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## **The clinical assessment of re-innervated motor function.**

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I, Tom James Hepke Quick confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

## ***Abstract***

### Background:

Muscle paralysis occurring due to nerve injury is a common clinical presentation. Re-innervation of skeletal muscle can occur spontaneously, or require surgical treatment. The return of movement after re-innervation occurs slowly, and never attains normal function (Birch & Quick 2016). Methods commonly used to assess this recovery of function have not changed significantly for over 7 decades. This study addresses the way re-innervated muscle function is assessed and how this might be improved.

Muscle re-innervation is in itself an important clinical aim; but, as muscle re-innervation occurs through a process of nerve regeneration, its assessment could also potentially present a method for study of this biologic process: That is to say that the clinical assessment of muscle function can be viewed as a surrogate for the success of nerve regeneration.

This thesis builds from a review of the historic approach to muscle assessment towards more modern methods for establishing validated outcomes for skeletal muscle motor re-innervation in humans. For use both as a research tool and as a nuanced clinical assessment for patients with nerve injury.

The traditional method used to assess muscle function has been to focus only on one aspect of force: the assessment of peak force, and to use a discrete ordinal assessment for this (the MRC, Medical Research Council grading of force). This approach is discussed in chapter three. A review of the historic literature (chapter two)

demonstrates that motor recovery is a complex phenomenon, and even in the area of peak force assessment; there is much to be improved upon. The benefits of utilising a continuous measurement of force rather than the discrete MRC scale are described, and then, in Chapter six, deployed in the clinical environment to examine outcome.

The characterisation of the severity of human nerve injury, in its vast variation, presents an unmet clinical challenge. There is no method available which characterises the injury in any way other than in a piecemeal way, and no method which standardises clinical outcome across the many modalities of nerve injury. To address this the operation of 'nerve transfer' is presented (in chapter 4) as an ideal 'standard model' for the study of human nerve regeneration. The history and development of nerve transfer are described and the utility of viewing this operation as a controlled experiment set out: Nerve transfer is a complete, intentional, iatrogenic, injury to a pure motor nerve with a single motor outcome. In this operation a nerve injury is created by disconnecting an expendable function to improve a more desirable function through the re-growth of nerves into this muscle. It is a discrete intervention which is undertaken to lead to an isolated improvement of a single assessable motor function.

The methods in current use to assess re-innervated muscle function are explored in chapter five where a cohort of international experts were invited to contribute. This study (n= 18) displays and describes the responses of national leaders in this speciality from 10 countries. The results show that MRC grade is the universal assessment standard, and yet this specialist group recognise the need for more in depth assessments of motor function. Only 17% (n=3) agreed that the MRC system was very useful for a thorough assessment of force, whereby 45% considered peak force to be



the most useful assessment of muscle function. There was acceptance of the method of using continuous force to assess maximal volition force.

Chapter six presents a study whereby the expert cohort agreement for the need for continuous assessment of peak force outcomes (from chapter five) are applied to a cohort of patients who have undergone nerve transfer to return elbow bending force. These data, have been published in the eminent peer reviewed Bone and Joint Journal (BJJ). This publication was recognised by peers as the first clinic based publication deploying a continuous measure of outcome for this procedure. The results demonstrate similar findings to the only other cohort study (Carlsen 2011) (where patients were assessed in an engineering laboratory). This study demonstrated validity of the clinical use of Hand Held dynamometry for assessment. The data described a population of outcomes whereby the mean was 7.2 KgF  $\pm$ 3.3.

If a continuous measure of force is to be the method used to (as presented in chapter six) to study the impact of any novel difference in care to improve outcome: It is important to determine the degree of improvement which would be characterised as clinically relevant. This concept is termed the Minimum Clinical Important Difference (MCID). There are many suggested methods within a wide literature on this subject and it is accepted that they return a widespread of responses. The calculations in this chapter have been based upon published methods and include recommendations from the IMMPACT (Initiative on Methods, Measurement, and Pain Assessment in Clinical Trials) consensus document, patient anchor data, expert Delphi and statistical distribution methods. The results of which have provide a wide range of MCID (from 793gF- 6.52KgF); such a spread of data is typical in research into this area.

Having taken the expert objective view that peak force is still considered a key outcome parameter; a study was performed (described in chapter eight) to explore the subjective experience of motor outcome. It has been explored whether peak force is an outcome considered relevant by patients. A questionnaire of satisfaction with outcome is undertaken with a group of individuals who have undergone muscle re-innervation (having had a nerve transfer to restore elbow flexion). The results of this are that the single outcome of peak force is *not* seen (by patients) as directly related to outcome nor correlated with the patients' satisfaction.

The results of the quantitative study in chapter eight are explored in more depth in chapter nine through a qualitative methodology: To explore the subjective experience in more depth a review of a group discussion between patient-participants was assessed in chapter nine; using the widely used methodological approach of phenomenology. These data highlight the 'lived experience' of motor recovery: highlighting the issue of fatigue, and also the problem of co-contraction. (Fatigue being the symptom of a feeling of loss of sustainability of force over time and co-contraction is a symptom of other muscles acting against the intended action to weaken the effect for a given force of another muscle.)

In view of the contribution from the subjective qualitative and quantitative studies (chapters eight and nine) the original study (chapter six) is revisited in chapter ten with a novel cohort and re-designed to include assessments of fatigue and co-contraction. Novel data regarding the function of re-innervated muscles was produced using the hand-held dynamometer assessment (as described in chapter six) in conjunction with surface EMG measurements. It was shown in this study that re-inner-

vated muscle has a lesser median EMG biceps frequency (-22.35Hz  $t=0.005$ ) suggesting a change in the muscle type from the normal controls. There was no difference in rates of co-contraction (-2.3%  $t=0.698$ ) in an unfatigued single maximal voluntary contraction. There was no sign of fatigue seen in the biceps under repetitive contraction (an accepted model of 3 sequential maximal attempts). Under sustained contraction (>80% maximal force sustained for 60seconds) the force was maintained in both re-innervated biceps and the controls. The degree of co-contraction in re-innervated arms under sustained force was greater than that of the controls (at 25.6% vs 15.6%) but this decreased to a normal level (14.5%) with fatigue (this change did not reach significance however  $t=0.101$ ). The re-innervated biceps were seen to fatigue however via a drop in the median frequency (-12.343Hz  $t=0.001$ ) prior to any such change in the control population of non nerve-injured muscles (3.15Hz  $t=0.343$ ). Thus demonstrating an earlier fatigue and pointing towards potential mechanisms for this via a change in the muscle fibre type (more fatigable) and a trend suggesting a contribution from afferent control and co-contraction.

## Methods:

A mixed methodological approach; of qualitative and quantitative methods, have been undertaken in this study. Chapters six and ten are quantitative assessments of outcomes in a cohort of patients who have undergone a nerve transfer to elbow flexion. Peak power is assessed in chapter six using a hand held dynamometer in chapter ten this is used in conjunction with surface EMG assessments. A Delphi method is used in chapter five to poll experts in the field on their practice and opinions of assessing motor recovery. The MCID calculations in chapter seven are undertaken by

an assessment of Qualitative data in a number of ways to quantify and estimate based on a number of approaches, this varied method widely used in the literature produces a spread of results.

## **Summary**

This thesis is a structured investigation of the key issues in motor recovery following nerve injury. The thesis is cyclical; and returns (in chapter ten) to, improve upon, the original study (chapter six) design to hone the question and produce a more informative, valid set of results; relevant to the patient cohort.

Re-innervated muscle function is a subjectively complex experience however there are themes of fatigue, co-contraction and pain which are not commonly assessed. Experts and patients agree we should move on from purely relying on the MRC 5 point scale to describe the complex phenomenon of re-innervation muscle function. It has been demonstrated that hand held dynamometry and sEMG provide a method to assess peak force, fatigability and co-contraction. This provides an assessment that correlates with the issues deemed most pertinent by an expert group and most relevant by a patient cohort.

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Contributions from Ashok Singh in Chapter six, Kevin Chang in Chapter seven and Hazel Brown, Kathryn Johnson and Anthony Gilbert in Chapter nine are hugely appreciated and credited in the text.

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“And such being the imperfect state of our knowledge; in the sound state of the nerves,  
it is not to be wondered at if our reasoning; respecting their disease,  
is very limited and fallacious”

Joseph Swan 1820

A Dissertation on the Treatment of Morbid Local Affections of Nerves:

# 1.

## Preface

### London 2017

The author is a peripheral nerve surgeon and has been a consultant in this field for five years. This thesis is the combination of a number of threads that have been stimulated by his clinical work towards improving patient outcomes in the area of motor recovery.

It is accepted that it is a flawed approach to consider any aspect of nerve injury recovery symptomology in isolation; any patient will clearly articulate this: The experience is that all the modalities of nerve function are inter-related. Restoring motor function to an insensate, or painful, body part has much less impact than improving all of the problems. To consider the problem in the round does little to allow focus on what can be improved. However; to study one has to dissect, to pull apart the features to study them first in isolation. To understand the parts in isolation is a necessary primary step, prior to attempting to comprehend the next layer of complexity when recombining those parts. This is an investigation of the isolated issues of motor recovery following nerve injury.

It occurred to the author in 2012 that nerve transfer would provide an ideal surgical model to study human nerve injury and all the subsequent chapters here have flowed from this first idea. It was thanks to a pump priming grant from the RNOH Charity that this work commenced and started first with the study via hand held dynamometer of a cohort of nerve transfers.

The author has learnt much on this past two-year period of part time study; a wider appreciation of the clinical and basic science literature, the essential steps of study design, of the importance of robust systems of data collection, of the benefits of true team work and of the character of himself and those around him. If these studies were to be run again they would be carried out in a very different manner with the knowledge that has been accrued.



## 2.

# Introduction to nerve injury

## 2.1 Challenges of nerve injury treatment

Peripheral nerves represent a huge anatomic concentration of functional ability; facilitating movement, sympathetic function and sensations of touch, temperature and pain. They are frequently damaged in trauma, from external agents, and also through misadventure by treating doctors and surgeons. The outcomes of recovery from these injuries are infrequently commensurate with pre-injury function or the patient's own expectations (Birch & Quick 2016).

The nature of human nerve injury means that the controlled binary animal experimentation models of injury; crush (Bridge 1994), transection (Batt 2013) or even stretch (Wall 1992) are not representative of the diverse degrees of injury or complexity of human outcome. In the complex interplay of random injury mechanism there are no standardised injuries. Nor is there any reliable method to absolutely assess the degree of injury, at the time of injury. Beyond these anatomic considerations (the impairment); the complex ways that humans react to physiologic and psychological disturbance (and how they express those problems to health care providers) mean assessment of nerve injury outcomes are mostly subjective.

Of all the functions of nerve; motor function (at first glance) appears to offer the most objective and assessable outcome: the ability of a muscle to contract can be measured in objective ways that sensation or pain cannot so easily. Studies of injuries to pure motor nerves could be envisaged, comparing differing techniques of repair or therapy regimens where the differential force outcomes of motor recovery are measured. The questions are still- have we chosen the correct objective motor measures, and do those objective measures reflect the patient experience?

In nerve recovery there are numerous objective and subjective outcome measures. The assessment of motor function has been isolated to the objective measurement of the peak force the muscle can generate. Subjective assessments of individual muscle functions are rare. However; general clinical assessment of function (or well being, or satisfaction) are often swayed by more pervading aspects of the recovery- underlying physiology, other injuries, other medical conditions rather than being specific to the limb which sustained the nerve injury in question. These scores often focus on the very isolated function or the very general assessment. Separating out the impact of the specific recovery of a re-innervated muscle to the overall subjective experience of the patients is complex (Birch & Quick 2016, Wang 2013).

It is a common report from many patients that any discussion regarding the importance of peak power does not translate to their day to day experience of function. They talk with much more 'texture' or 'depth' in their description of the experience of motor recovery than objective assessment has the ability to detect.

## 2.2 Historical development of nerve injury understanding

The form and function of nerves have interested man and attracted study for the earliest days; Herophilus (*Staden 1989*, p159) demonstrated in the third Century BC that motor and sensory nerves roots were separate. Galen described the course that sensory nerves follow from cortex down to the digital nerves, but he also wrote that 'once divided they could not be repaired' (*Little et al. 2004*). From these early historical assessments followed the widespread recognition of the nerves as the tissue which control movement and sensation leading to the subsequent recognition that they are amenable to repair after injury:

It is interesting to take up the modern story of nerve surgery in London, with William Cruickshank (who was an assistant to William Hunter). In 1776 Cruickshank was tasked to undertake a number

of experiments dividing the Vagus and intercostal nerves in dogs. He excised a piece of 'some 15mm in length' (Ochs 1977) at 'differing lengths' along their course.

In two of these experiments the animal survived for several weeks and he found on subsequent autopsy that "when a portion of nerve is removed by incision its place is supplied by blood and lymph, which first becomes vascular and organised, and is afterwards converted into a substance of the same colour as nerve" Illustration of this tissue was presented to the Royal Society by John Hunter on the 13<sup>th</sup> June 1776.



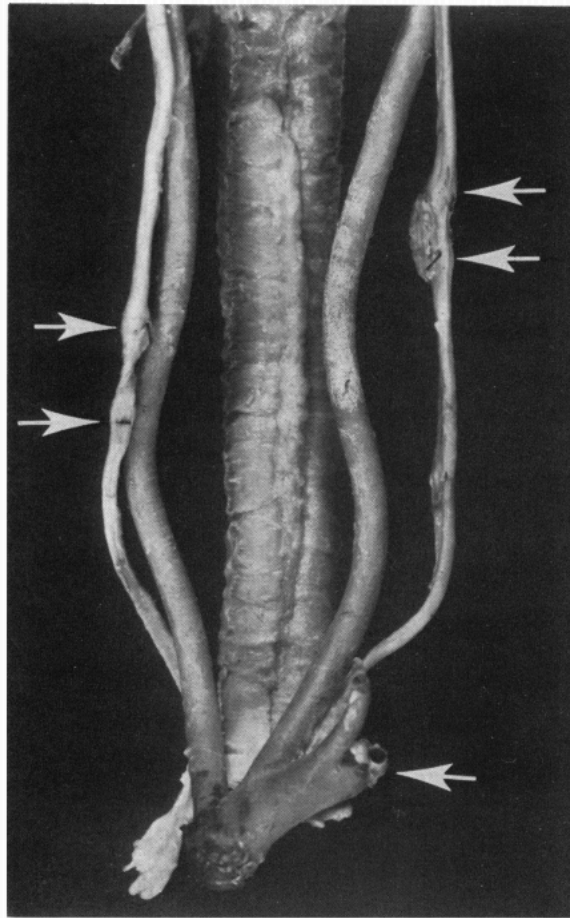
**Figure 2.1:**

Illustration plate from Cruickshank 1795. Marked as

"Figure shows both the complete reunion of the nerve after division and its regeneration after the loss of substance."

In a later report (Cruickshank 1795) he recorded in his own words...

*"The divided nerves were united by a substance of the same colour as nerve . . . and the extremities formed by the division were still distinguished by swellings in the form of ganglions . . . (thus) I found the nerves regenerated, a circumstance never hitherto observed."*



**Figure 1**

Cruikshank's preparation showing regeneration, preserved in Hunter's museum. The arrows on the right side show swellings above and below the previously cut trunk on the right. The preparation has been photographed from the posterior view. The nerve on the left which had been divided later also has arrows placed at the swelling near the original cut ends. Also shown by some of the arrows are the black pins inserted by Hunter. The lower arrow on the right shows the arch of the aorta with the carotids ascending on either side of the trachea. (Reproduced by courtesy of Mr. Donald F. Hays, Royal Infirmary, Glasgow.)

**Figure 2.2:**

A figure taken from *'The early history of nerve regeneration beginning with Cruikshank's observations in 1776 by Sidney Ochs'* (Ochs 1977) showing a reproduction of the prosection in the Hunterian Museum on which the illustration Figure 2.1 is based.

This work was challenged at the time, and went unpublished for many years. Interestingly though it led directly to another advance in nerve regeneration understanding when, in 1778, Father Felice Fontana visited Hunter's laboratory. He met Cruikshank whereby they discussed his experimental findings. Fontana then undertook similar work (excising sections of the Vagus nerve in rabbits) and using the new advances in 'microscopic study' was able to show that the material [that

regenerated] between the cut nerves demonstrated the characteristic spiral banded appearance of nerve (Skinner 1788).

The story continued in London (in 1795) when John Haighton (a physiologist and physician) continued similar work on dogs. One of Haighton's subjects survived 6 months and over this time regained the ability to bark, which had been silenced by division of branches of the Vagus nerve in the neck. At 19 months following nerve lesion an autopsy specimen was examined and described to show a 'neuromatous swelling'; but Haighton did not undertake any microscopic examination of the tissue. The two cases were represented to the Royal Society and the concept of the ability of nerve tissue to repair across short gaps started to gain acceptance.

This was furthered when a paper presented by Joseph Swan in 1820 at the Royal College of Surgeons was awarded the Jacksonian Prize. In "On the Treatment of Morbid Local Affections of Nerves" (Swan 1820) Swan first gives support to the galvanic theory or electric function of the nerves

*"the galvanic influence on the nerves of an animal apparently dead, will produce the same motions in the parts to which these nerves are distributed, that were produced in them when the animal was alive"*

*"we know that when a part has been deprived of the nervous influence by its communication with the sensorium being intercepted, the functions of the part of which the nerve is disturbed are suspended and are incapable of being reproduced until the divided portions of nerve have become reunited, except through electricity; but beyond this we know little"*

Swan describes how he followed the motor recovery of dogs following sciatic nerve division where he noted that only in short gaps [not defined] was regeneration possible but he did not follow this forward to an argument to support suture repair.

*“When a nerve has been divided, reunion in course of time generally becomes perfectly established, so that it performs its functions as well as if no division had ever taken place. When a portion of a nerve has been removed, and especially if it be a large portion, the breach is with the greatest difficulty, if ever repaired, when it happens in the case of a nerve of the largest size. For instance, when a portion of the sciatic nerve has been removed, the separation of the divided extremities is very extensive, the superior portion prepares for the reunion by an increased vascularity; but though the inferior does so it is in a much less degree; and after a time this vascularity is very greatly diminished, and the restorative process appears at a stand.”*

The scientific demonstration of the principles of nerve regeneration and repair seen in animals were not accepted by those treating human disease though. G.J Guthrie (a surgeon active in the Napoleonic wars) in his 1827 text *“Treatise on Gunshot Wounds and Nerve Injuries”* that: He knew of *“no case in man of recovery of function after division of a main nerve”*. The belief, pervasive in clinical medicine and surgery at that time, was that there was no benefit in trying to repair an injured nerve. This view appeared to be supported by experimental findings by Neurologist Albert Eulenburg and Leonard Landois, a physiologist. They reported from their experiments (*Eulenburg Landois 1865*) on many differing animal models of division and end to end nerve repair that function did not return immediately following anatomic nerve repair. They stated that nerve suture is ‘positively dangerous’. Considering the suture material provides a ‘hindrance to regeneration’. The expectation of immediate restoration of function is clear in their work and that of their peers. It is most likely that this time delay (from repair to recovery of function), which we now know is necessary for nerve to regenerate to its distal target, meant that successful outcomes so often evaded detection.

In America (during the Civil war) a well renowned surgeon; Silas Wier Mitchell, saw significant clinical benefit from nerve repairs by suture and described (*Mitchell et al. 1864*) the means by which he considered it should be carried out. However, through the 1800’s across the whole

western world there was very little acceptance of any utility of nerve repair. Mainly; it seems, again due to the fact that physiologic function did not immediately return following nerve repair.

The first steps to considering the mechanism of regeneration (and thus to comprehend the necessary time lag to recovery) came when microscopic analysis of nerve tissue was undertaken. The study of neural micro-pathology by Thodore Schwann (Schleiden 1839), Franz Nissl (*Franz Nissl 1898*), Heinrich Waldeyer (*Waldeyer 2009*), Camillo Golgi (*Golgi 1995*), and Carl Weigert (*Weigert 1897*) slowly focused understanding. However until Waller's treatises on '*Experiments on the section of the glosso-pharyngeal and hypoglossal nerves of the frog and observations on the alteration produced thereby in the structure of their primitive fibres*' (Waller 1843) were presented at the Royal Society in London (1901) did the time delay in nerve degeneration and regeneration start to be understood in the English medical establishment. This was further advanced as the work of Santiago Ramon y Cajal became available in the English literature (*Cajal 1928*).

Therefore; piece by piece, the natural history, microanatomy and physiology of nerve injury came together. It became accepted that unlike any other biologic system's recovery; peripheral nerve regeneration was dependent on a large time lag. The frustration with the delay to recovery is evident still today (as the lived patient experience demonstrates in chapter eight). These developments which reset the expectations for outcome set up the development of the future surgical techniques:

## **2.3 Development of surgical nerve repair techniques**

First, the concept of primary nerve repair (suturing cut ends directly back together) was developed and subsequently improved upon as the fascicular pattern of the internal topography of the nerve was understood (mainly through the work of Sunderland Sunderland 1945; Sunderland & Ray

1948; Sunderland. 1959). The challenge of the 'nerve repair gap' (where the cut nerve ends cannot be apposed without tension) was addressed by Huber in the US medical corps in World War I. Investigating autograft (nerve transplanted from elsewhere in the body) allograft (nerve transplanted from other people) and xenograft (animal nerve tissue) to bridge these gaps. This experience was applied in civilian practice by Seddon (1947) who's reported satisfactory results of autograft nerve in between 38-52% of his cohort and Millesi (who's 42 years of grafting experience was reported in 1993 (Millesi 1993). This widely popularised the application, utility and efficacy of 'nerve grafting'. Thus; from these foundations the clinical speciality of peripheral nerve surgery grew. From work performed in the war (Millesi 1990; Penkert & Fansa 2004), this knowledge and expertise was disseminated across civilian practice in the western world though the 1950's; the primary challenges were now to develop classification systems, a lexicon of disease and building clinical experience. The speciality was at a proof of concept stage of its development. The exponents still met much resistance to the thought that intervention in nerve injury could offer the patient benefit. The practicalities of the surgical procedures and the academic approach to this work underwent a great evolution to reach the state of the art today.

The last step to bring this story of surgical advance up to date has been the widespread uptake, over the last decade, of a further technique; that of nerve transfer. This story of nerve transfer (using axons originally destined for one muscle, with expendable function, to re-innervate directly a more proximal muscle) has run parallel to the more traditional approach of nerve grafting. Nerve grafting aims to recreate continuity to a damaged nerve, nerve transfer looks to reconstruct it by 're-wiring' it with another nerve. This is not a new concept; In 1903 Harris and Low (Harris & Low 1903) described the implantation of the distal stump of an injured upper trunk, in an end-to-side fashion, to the root C7. They discussed the technique but did not provide the outcome. There were other early reports of nerve transfer (Tuttle 1913, Feiss 1912), but as previously befell the reports of repair; these were reported without sufficient follow-up were considered a poor option, and gained no traction in the profession. In 1963, Seddon reported the successful re-innervation of the biceps muscle with a nerve transfer from two intercostal nerves (using a denervated ulnar



nerve as a graft) At a year follow-up, the patient had regained 'some active flexion' of the elbow. In 1994, Oberlin et al described the use of an ulnar nerve fascicle to re-innervate the biceps muscle, directly; Avoiding the need for a nerve graft. This technique was widely adopted as a powerful tool for returning function to elbow flexion and has been modified by many (Liverneaux et al. 2006; Thomas H Tung 2003). The era of improving nerve injury surgery outcomes has started. The ability to deliver axons close to a muscle when its own nerve has been damaged allowed quicker return of function. This method has been widely adopted now and has many applications in nerve injury reconstruction.

## 2.4 Challenges for the speciality of nerve surgery

Nerve injury surgery has now been accepted as a recognised field of surgical care where the specialities of Neurosurgery, Plastic and reconstructive surgery and Orthopaedic surgery overlap. Today there is an active international nerve injury community who agree on much: The methods of assessment, the requirement for intervention in the unfavourable degenerative lesion, and the methods of supportive care necessary to gain the most from the period of rehabilitation.

There are however now new challenges. The current state of the art is represented as follows:

“[Current] assessment of outcome is often blunt and simplistic focusing on motor and sensory outcome” (Novak et al. 2009).

The wonder in the success of nerve repair and reconstruction and the complexity of the function of nerve has led to the commonly held simplistic view of assessment.

“From a surgeon’s perspective, the goals of surgery have largely focused on the return of motor function and restoration of protective sensation.” (Bengtson et al. 2008)

More recently, the trends in outcomes research after nerve injury have been directed toward more functional results and patient-reported outcomes.

Christine Novak goes further saying:

“Patient-reported outcome and disability using valid and reliable measurement tools are rarely included in published reports, and few studies have evaluated functional outcome or health-related quality of life after peripheral nerve injury.” (Novak et al. 2009)

The use of quality of life (QoL) measures to quantify and describe the morbidity created by brachial plexus injury is growing and starting to be integrated into the lexicon of study in this area (Kitajima et al. 2006; Choi et al. 1997; Ahmed-Labib et al. 2007; Franzblau 2013).

QOL measures have had their validity measured as an outcome. There are none though specific to brachial plexus injury recovery; nor are there any which are validly reflective or necessarily reactive to the fields of change that the patient experiences. The specificity of an outcome measure can only come from having their design informed by patient experience and expert opinion. To develop an outcome assessment requires an idea of what is thought of as a significant change is necessary. When these measures have been agreed and characterised it is important to define minimal clinical important difference (MCID) for these scales. MCID is a concept which sets the minimum reactivity of an outcome measure and as such is a key concept in designing such an outcome measure. It is also central to determining a power analysis for the proper design of a prospective trial (Wright et al. 2012).

These advances in defining and characterising meaningful and responsive outcomes are necessary to facilitate, support and assess the next stage in the evolution of therapeutic modalities (conduit design, biologic manipulation of inflammation, personalised medicine, genetic therapy etc.) for nerve injury treatment.

## 3.

# Introduction to the surgical model

The following is an introduction to the nerve transfer to re-animate elbow flexion which has been used throughout this thesis as an experimental model.

### 3.1 Background

Human nerve injury is a complex pathology. The challenge to compare outcomes in nerve injury is made more complex by the fact that the initiating injuries are often so diverse and it is currently impossible to sensitively detect with specificity the specifics of the injury. Across any nerve there are tens, if not hundreds of thousands of neuronal axons. Each of these can be injured in degree of severity. This complexity can not be easily diagnosed nor characterised and its recovery will rely on varying factors; such as the degree of the local tissue injury and the response of this tissue in repair or scarring.

Nerve injury creates changes in the efferent functions of; sweating, hair growth, muscle bulk tone and volitional contraction, and the afferent functions of; proprioception, pain, light touch and temperature. The neuronal axons (that are in their tens or hundreds of thousands in most nerves) which make up the functional aspect of the nerve can be injured in a wide variety of degrees. From the binary state of 'neurotmesis' or complete nerve division (where all the of axons have been incised along with all the supportive tissue) to the non degenerative conduction block lesion (where there is physiologic dysfunction but anatomic continuity of all the constituents of nerve). There is, between these two extremes, a wide spectrum of degrees of injury which can befall each individual of the myriad axons within the nerve, each with a differing outcome. The exact numbers of axons which have suffered each grade of severity is impossible to determine at the time of

injury. Thus exactly quantifying the severity of any 'wild type' or non-experimental nerve injury is not currently possible.

In addition to this, other tissues are often injured in association with the nerve tissue- vascular injuries, muscle damage, joint dislocation and fractures all make it more difficult to dissect the contribution of the nerve injury to the clinical situation from the other factors.

On top of the fact that human nerve injuries are (even in isolation from the other concomitant injuries), often too complicated to grade at the time of injury, there is the added complication of the long time periods necessary for recovery. Success of motor re-innervation reduces with time (Wu 2014) and in humans can continue to be possible up to 18 months after injury (Elkington 1944) and clinical experience suggests sensory re-innervation is possible for even a year or so after that.

There are no perfect outcome measures for nerve injury, the ones that have been used regularly for assessment address only a small part of the interrelated whole. Visual Analogue Score (VAS) pain assessment and Medical Research Council (MRC) motor assessments are the two most widely used outcome measures and neither of these are close to ideal measures.

Thus if one were to assess the naturally occurring nerve injury it would only be those complete injuries of nerve (neurotmesis) that could be standardisable. These injuries, being incisive, have other associated tissue damage around the area of injury. The location of the injury will be hugely variable, the amount of function affected by the injury variable and all of these variables uncontrollable. Further the psychology of the individual patients; in terms of concepts such as engagement, activation, catastrophisation and kinesophobia have all now been shown to be strong affectors of outcome (Monticone 2013, Bright 2014, Sullivan 1998). Thus taking all of this together, when assessing median nerve lacerations amenable to primary repair as a group (even when combining multiple series (Birch & Quick 2016) in order to assess motor recovery, sensory recovery and pain (and perhaps also assessments of sweating and proprioception) the groups will be

so varied as to offer little ability to compare or control for any of the variables other than for rather general statements to be made.

It is accepted that human peripheral nerve regeneration is inferior to that in the mammalian models that are studied (Höke 2006). Transferring the advances made through animal experimentation to trials of safety (then efficacy) in humans presents the next challenge. To advance such studies a standardised nerve injury model is needed in humans. An ideal operation would be one where a complete nerve injury is created at a standard distance from a target organ where its re-innervation can be easily assessed. Ethical concerns arrest any wish to undertake this on un-injured people but the operation of nerve transfer provides such an opportunity for 'experimentation' to be undertaken which is analogous to the animal models.

The first nerve transfer animal experiments (cross innervation) were reported by Buller (1960). This paper identified that the characteristic of a re-innervated muscle (particularly the type of energy supply for ATP re-synthesis -whether glycolytic or oxidative) is determined by the nerve supplying it. Needham (Needham 1971) developed this idea further and demonstrated across a number of studies, how (after re-innervation) these differing types of muscle (type I, type IIa and IIb muscles<sup>1</sup>) become much less different from each other, the changes taking place mainly in the IIb, both as regards to weight loss and enzymatic constitution.

Nerve transfers to re-innervate elbow flexion in humans return an essential function: to move the hand in space (specifically to bring the hand to the face and mouth). From the point of view of

---

<sup>1</sup> Type I fibres are slow twitch, have low ATPase activity (\*at pH 9.4), and have high oxidative and low glycolytic capacity, and are relatively resistant to fatigue. Type IIA fibres have high myosin ATPase activity\*, are fast twitch and have high oxidative/glycolytic capacity. They are relatively fatigue resistant. Type IIB fibres have high myosin ATPase activity\*, respond with a fast twitch, have low oxidative and high glycolytic capacity. They fatigue rapidly.

assessing motor outcomes elbow flexion is an easily assessable function; The elbow can be modelled as a simple hinge joint and in comparison to other muscles (such as prime movers of the shoulder or the fingers) its activity is directly relatable to a simple uniplanar recordable movement.

Nerve transfers are a nerve injury created de novo by the surgeon in a functioning nerve (Oberlin 1994). The surgeon cuts functioning parts of a nerve (whereby the loss of this function is tolerable) to use these axons to renerivate a muscle with an essential function [Figure 3.1]. This is a controllable injury- it is a complete injury (that is to say all the axons complete neurotmesis) and it is made at a known distance from the target muscle. The recovery is intended to be pure motor recovery. It is performed with little local tissue damage and is akin to the early experimentation (Needham 1971, Buller, et al 1960). We would expect the same muscle type changes that have been documented in animal models (Needham 1971) but the effect on muscle type has not yet been shown in humans. It would be expected that this re-innervated muscle would demonstrate signs of this change and have a different threshold for fatigue due to it (this is assessed in chapter ten).

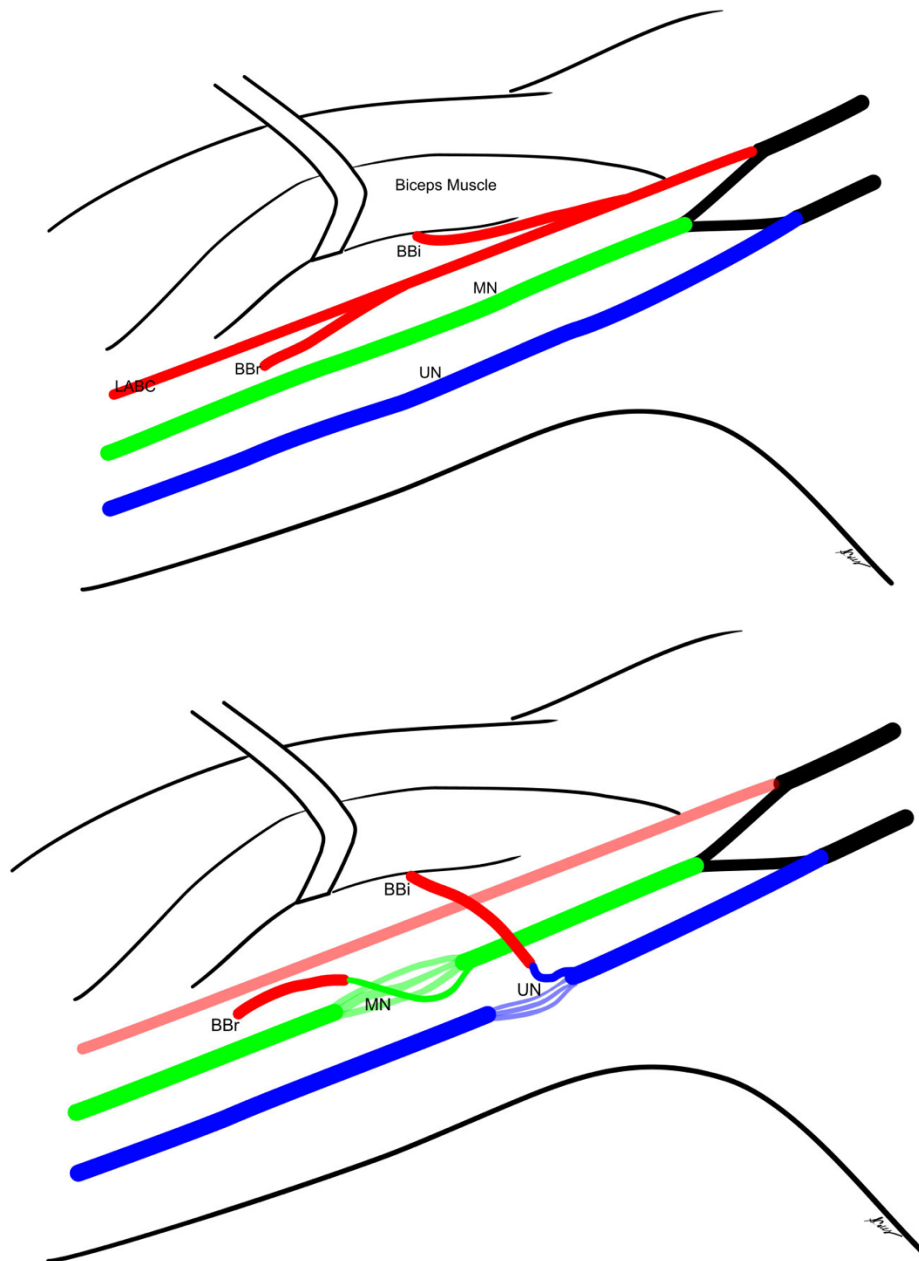
### **3.2.1 Technique of the model used**

This nerve transfer is named after the surgeon who first described it in detail (Oberlin et al. 1994). The operation is to first confirm that the musculocutaneous nerve has sustained a degenerative injury and is non-functional. Then, in order to identify sacrificable axons, intact uninjured nerves are incised into and the constitutive fascicles are dissected free. These functioning nerve fascicles are then examined with stimulatory electric currents to assess their function. One or two are selected as supplying a function which can sustain their loss. These fascicles are then divided (complete nerve injury) and redirected to grow in to the motor components of the denervated distal stump of the musculocutaneous nerve. This then over time results in the re-innervation of the function of elbow flexion. The original single nerve transfer re-innervates one of the muscles of elbow flexion (biceps). There has been a subsequent advance on the technique where both biceps

and brachialis are re-innervated.<sup>2</sup> The technique that is used as the surgical model in these studies of re-innervation of elbow flexion is that of the double Oberlin transfer (or the Leechengongs).

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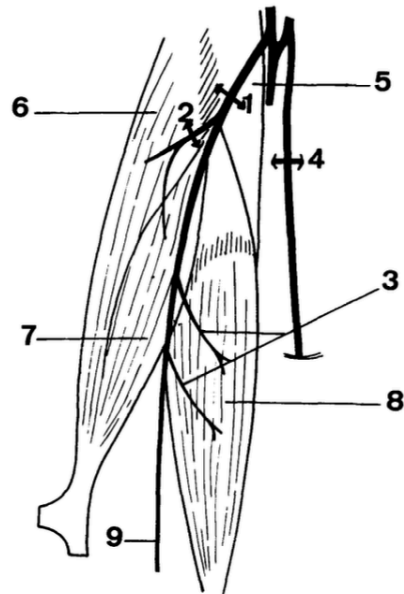
<sup>2</sup> This technique of a double transfer was first described (it now seems) by Somsak Leechengongs and subsequently by Susan Mackinnon (this 'race to publish' produced a rather famous surgical spat published in the literature (Mackinnon 2006)).



**Figure 3.1**

Graphic representation of an Oberlin transfer- Pre op above – operative procedure below–Where the musculo-cutaneous nerve (red) to biceps BBi and brachialis BBr are not functional and fascicles from the functioning (blue) ulnarUN and (green) median nerves are used to re-innervate the function of elbow flexion.  
 .Taken from: *Nerve Transfer for Restoration of Elbow Flexion in Upper Brachial Plexus Injuries*. *OrthopaedicsOne Articles*. In: *OrthopaedicsOne - The Orthopaedic Knowledge Network*. Created Sep 19, 2011 09:04. Last modified Oct 06, 2013 14:20 ver.7. Retrieved 2018-01-23, from <https://www.orthopaedicsone.com/x/sYAaB>.

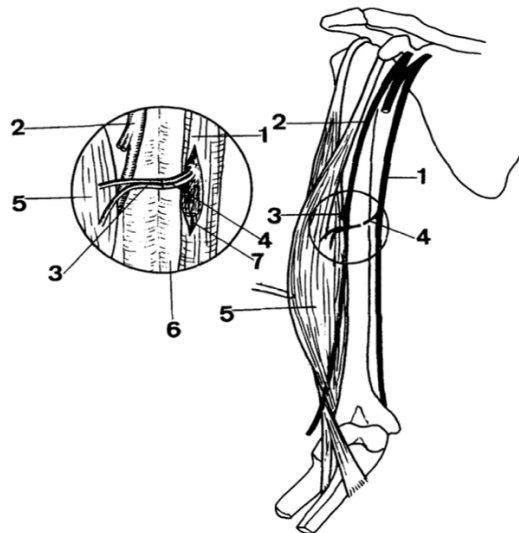




**Figure 1.** Drawing of a right musculocutaneous nerve and its branches to biceps muscle and brachialis muscle. Arrows indicate the sites of cross-sectional samples with regard to the morphological study. 1, Musculocutaneous nerve; 2, branch to the biceps muscle; 3, branch to the brachialis muscle; 4, ulnar nerve; 5, coracobrachialis muscle; 6, short head of the biceps muscle; 7, long head of the biceps muscle; 8, brachialis muscle; 9, lateral sensory branch of the forearm.

**Figure 3.2**

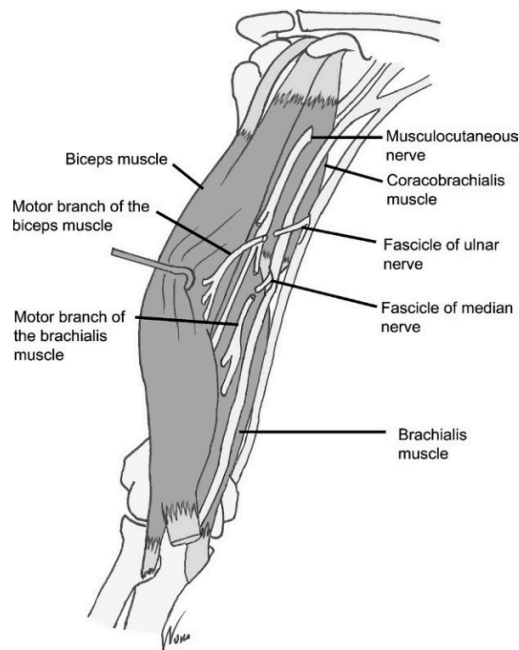
A reproduction of the anatomic study which led to the Oberlin transfer (Oberlin et al. 1994) p233



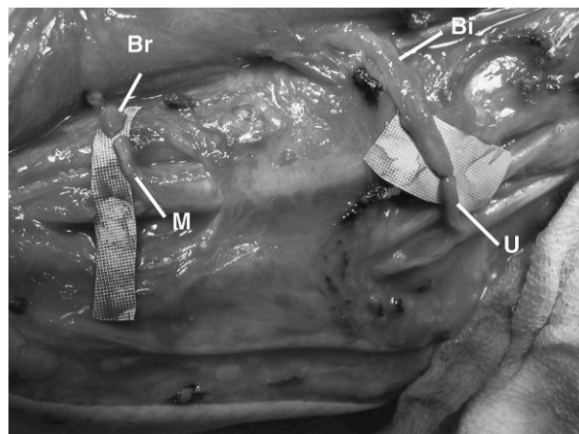
**Figure 2.** Transfer of part of the functioning ulnar nerve into the motor nerve of the biceps. The nerve suture can be performed before or within the brachial tunnel. 1, Ulnar nerve; 2, musculocutaneous nerve; 3, branch of the musculocutaneous nerve to the biceps muscle; 4, two fascicles harvested from the intact ulnar nerve; 5, biceps muscle; 6, brachial tunnel; 7, epineurium of ulnar nerve.

**Figure 3.3**

The original description of the Oberlin transfer (Oberlin et al. 1994) p234



**FIGURE 1.** Principles of the technique of the double nerve transfer to restore active elbow flexion: 1 fascicle of the ulnar nerve is sutured to the biceps branch of the musculocutaneous nerve. One fascicle of the median nerve is sutured to the brachialis branch.



**FIGURE 3.** One fascicle of the median and ulnar nerves has been selected and distally divided. The biceps branch has been dissected, traced into the musculocutaneous nerve, and divided. The brachialis branch has been dissected, traced into the musculocutaneous nerve, and divided. Abbreviations are explained in the legend of Figure 2.

#### Figure3.4

Intraoperative picture and diagram of the technique of double transfer from (Goubier & Teboul 2007)

### **3.2.2 Rehabilitation and recovery of function**

Following a nerve transfer; patients are immobilised for six weeks in a sling twenty-four hours a day. When this period of immobilisation has finished patients are then rehabilitated from the secondary joint stiffness (created by this immobilisation necessary to protect the nerve repair). There then follows a set protocol for rehabilitation of the arm and specifically the function of elbow flexion. This process utilises the concept of cerebral plasticity whereby the brain can relearn to use this re-assigned function. That is to say to correctly use the axons that used to command wrist flexion but that now bend the elbow.

The return of innervation to the biceps and brachialis muscles occurs following the regrowth of the axons from the transferred fascicles from the nerve repair, down the de-innervated distal nerve stump to the muscle. Following this ingrowth, and the re-establishment of motor endplates, contraction is possible. In parallel with the efferent (out going messages) re-innervation there is also a cohort of afferent axons also re-growing.

The arrival of the axons at their distal targets is difficult to assess and thus place a definitive time period on. The efferent fibres are only liable to contract when the patient has volition control over the transferred function and is liable, thus to a clinical assessment lag (Kakinoki et al 2010) in assessing the differences between intercostal and Oberlin transfers to biceps noted that the time to MRC 1 function in the Oberlin group was 9.8 weeks and MRC grade 3 by 36.8 weeks.

The afferent pathways were investigated by Lee et al (2015) in a study on the tender muscle sign (TMS). They studied 31 patients with a variety of differing nerve transfers in a retrospective review of prospectively collected data. They assessed the presence of a deep tenderness and noted that it preceded and predicted return of volitional contraction. They noted that the TMS sign was positive 2-7 months prior to any palpable muscle contraction was evident.

## 4.

### An introduction to motor function, and its assessment

A review of the literature on the history and future of Motor Outcome assessment.



*Fig. 14 BICEPS (Musculocutaneous nerve; C5, C6)*  
The patient is flexing the supinated forearm against resistance. *Arrow:* the muscle belly can be seen and felt.

**Figure 5.1:**

Taken from Fig 14 of Aids to Examination of the peripheral nervous system, Medical research council memorandum No 45 (superseding War Memorandum No7) Her Majesty's publishers. 1976

The following is an introduction to the discipline of clinical assessment of motor recovery pertinent to the measurement of outcomes following re-innervation.

## 4.1

The clinical experience of nerve injury involves many aspects which are subjective in nature; not easily objectively gradable: One example is the experience of pain. It is a very personal experience and can in truth never be assessed by another. “Is it possible, in the final analysis, for one human being to achieve perfect understanding of another?” (Murakami 2011). But one can, as an observer, recognise signs that a fellow human is in pain (Cowen et al. 2015) and indeed, this empathetic assessment is frequently used to grade young children’s pain (Slater et al. 2008) and others who cannot comprehend or communicate their suffering (Herr et al. 2006).

The objective assessment of movement seems to be, at first glance, a much more straightforward task. Movement is easily seen by an observer and can be graded. A simplistic assessment would presume that the observation of a movement is not so different to the subjective experience of a movement. Many movements are straightforward to initiate, requiring no conscious effort; that they occur almost without willing them. Yet even this assessment of observed or measured motor function has encountered challenges.

The recovery of motor function following denervation (occurring naturally or after surgical intervention) is a slow one; From a long period of flaccid paralysis to the first flickers of volitional contraction to a plateau of functional gain takes months. In objectively assessing development of this recovered muscle function, force has become the ‘headline figure’. Other aspects of force such as; sustainability and fatigue, control and proprioception, grade-ability of increase or release of force have been overlooked or ignored. Beyond this even the assessment of muscle force has become simplified. Force has been equated solely and synonymously with maximal voluntary contraction (MVC). Manual muscle testing (MMT) of MVC has been established by consensus over generations of clinicians as the uni-modal assessment of choice when assessing this important characteristic of neurologic disease.

There has been a recognition, present since early history (having been recorded over 3500 years ago in Genesis 32 (Hoenig 1997) of the importance of the assessment of muscular wasting, paralysis and weakness from nerve injury. There is a good review of this history in, a historical essay tracing the 'history of scoring and assessment of neuromuscular weakness as part of daily neurological practice' written by Dyck (2005).

The first modern record of a scale to try to assess weakness from neurologic dysfunction was published by Mitchell and Lewis (1886) in the United States, this collaboration between a celebrated American Civil war surgeon (Silas Weir Mitchell) and Neurologist (Morris J Lewis) sets the tone for the driving power of military experience and multidisciplinary collaboration which is seen continued unto the modern day. In their report (Mitchell & Lewis 1886) on 23 patients with 'posterior sclerosis' of the spinal cord they were not only the first to describe how to elicit a tendon reflex but also they also were the first to describe an alpha numeric scoring system - scoring the ataxia from this upper motor neurone lesions as

Class 1: normal

Class 2: slight impairment,

Class 3: great impairment,

Class 4: paralysis

With further reference to muscle reflexes (an assessment of the muscle control arc) scored as 0 (absent) = (very slight) - (slight) N (normal) + (marked) and + + (very marked).

The next recognised step forward came from the Mayo Clinic in Rochester where according to research by Dyck (2005) the work of Henry Plummer from 1910 at this clinic extended the use of a ordinal numerical scale and the use of + and - for muscle weakness. Their scale (still used in many American institutions) begins with 0 (normal) then -1 weak, to -4 (being absent). This scale did not appear in publication until 1956 (Bastron 1956).

Wilhelmine Wright writing in the Boston medical and surgical journal in 1912 (Wright 1912) regarding her experiences of Polio in Boston and in Berlin writes of her 'rough method' of classifying the muscles according to the amount of resistance they can overcome is the following :—

1. Muscle capable of overcoming gravity and outside force—normal.
2. Muscle capable of overcoming gravity alone—good.
3. Muscle capable of overcoming friction of joint and table—fair.
4. Muscle capable of overcoming friction only when assisted—poor.
5. Muscle incapable of any contraction—bad.

Robert Lovett a Professor of Orthopaedic Surgery in Boston Mass. USA, published his rather simplistic no- numerical rank scale in 1916 (Lovett 1916).

Fair (able to move against gravity) and

Good (able to move against resistance).

In 1939 Kendall and Kendall (H. O. Kendall et al. 1971) when assessing the motor loss and recovery in cases from the Polio epidemic they empirically graded a manual assessment equating *fair* with 50% strength and *good* with 80% strength.

The assessment of manual muscle testing was advanced under the Chairmanship of the Medical Research Council committee 1941 of Brigadier Riddoch in the pamphlet "Aids to the investigation of peripheral nerve injuries (war memorandum no 7)" HMSO, London (subsequently revised in 1943). The MRC scale was established as a post war tool for manual muscle testing (MMT) to grade the recovery of nerve injuries, (rather than as previous scales have been addressing deteriorating medical neurology).

Thus the improvement from paralysis the scale starts with 0 for no function and progress upwards to 5 for the measurement of peak Power.

0 No contraction

1 flicker or trace of contraction

2 Active movement with gravity eliminated

3 Active movement against gravity

4 Active movement against gravity and resistance

5 Normal power.

This publication's popularity and worldwide recognition is most probably due to its simplicity, and educational illustrations on how limb muscles should be tested (see picture 4.1). Various versions of the MRC report have subsequently been published that have aimed to improve the methods for muscle examination. The revision of this work in 1976 "MRC Memorandum No 45. (superseding War memorandum No7) Aids to the examination of the peripheral nervous system", HMSO, London (Committee medical 1976) includes recognition that

*"Grades 4-, 4 and 4+ may be used to indicated movement against slight, moderate and strong resistance respectively" (Committee medical 1976)*

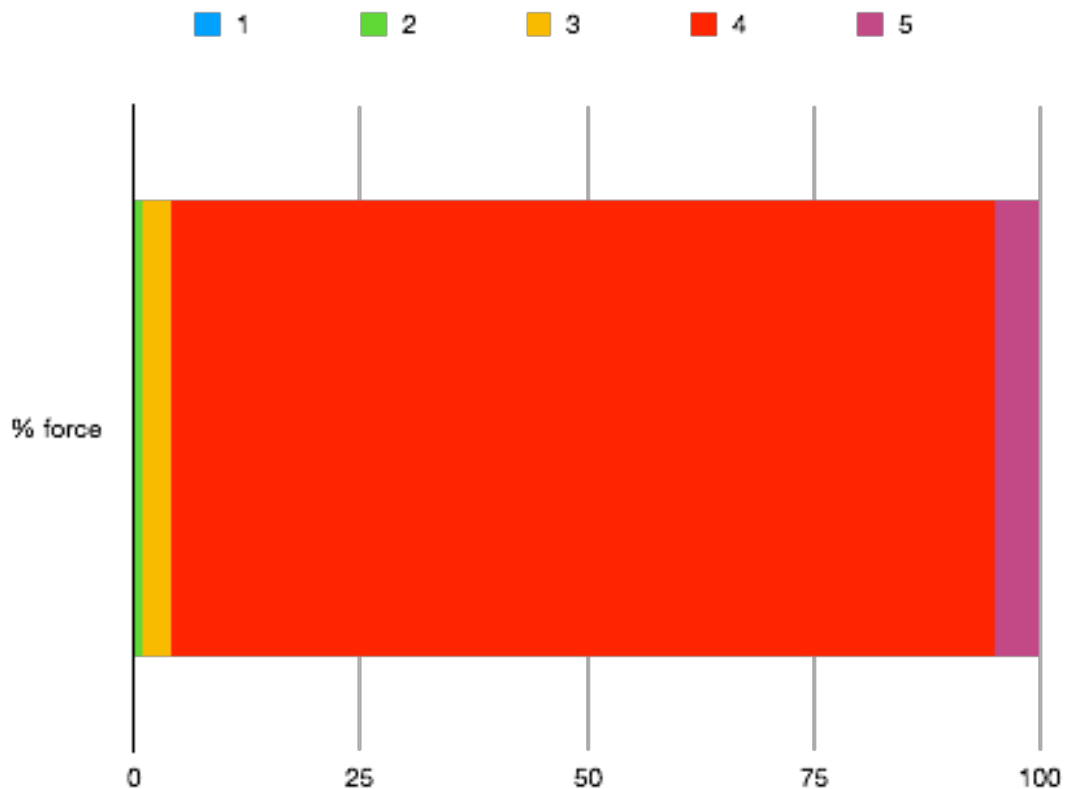
It is this scale that has held a pre-eminent position in muscle force assessment clinically and in research outcomes for the past three generations. The author has conducted a recent review [Chapter 5.5.1] of leading clinicians (n=18) across the world on their preference for recording muscle force and 100% used the MRC system. The MRC system has been central to international medical education for it is easy to understand and (until the introduction of the arbitrarily assessed graduations of slight, moderate and strong resistance with grade 4) highly reproducible and valid. The most recent (2010) edition of 'Aids to the Investigation of Peripheral Nerve Injuries, Medical



Research Council: Nerve Injuries Research Committee' starts with a historical review and appreciation for its application over the years (Compston 2010).

In 1983 Kendall and McCreary (F. P. Kendall & MacCreary 1983) revisited the work of Kendall and Kendall in the 1940s within the 0-to-5 scale. They equated 4/5 strength with a level of force called 'good' and suggested (with out clear justification) that this should be considered as representing 80% of full strength. None of these estimations of force seemed to relate to the descriptions given in the MRC system.

This clash of an empirical feeling of what 'good' and 'fair' outcomes are and how these lie within the agreed classifiable boundaries (MRC) sat poorly together. What was needed was a clarification between what researchers and clinicians thought was good and fair and what the demonstrable boundaries (as flawed as they were) demonstrated. This clarification came from MacAvoy in a robust cadaveric biomechanical analysis (MacAvoy & Green 2007) that 4% of a muscle's possible range of force is required for function against gravity. From this work; MRC 4 can be equated to a statement that it is "at least 4% of full force". Further if MRC 5 is taken as 95-100% then 91% of power range is contained within MRC grade 4 (MacAvoy & Green 2007). The following graphic represents this distribution.



**Figure 4.2.**

Graphic representation of distribution of percentage muscle force required to attain differing levels of MRC assessed Force. Based on MacAvoy & Green 2007.

Despite being a cardinal feature of daily neurological practice (and long before MacAvoy's study), it had been recognised that the MRC scale was not an ideal too, perhaps due to this inequity of its categories (with Grades 1, 2 and 3 being too narrow, and 4 being too broad) being appreciated. This led to many attempts to modify the scale (Brandsma et al., 1995; Dyck et al., 2005; Cuthbert and Goodheart, 2007; MacAvoy and Green, 2007; Merlini, 2010). Many adding sub divisions 4-, 4, 4+, or starting to quantify within the grade of 4 the ability to lift certain given weights. These attempts however well intended still do not provide the ideal continuous scale for assessment of maximal muscle force.

All of the scoring systems described (whether; (normal, good, or fair) (5, 4, or 3) or including + or - grades) are subjective descriptions of strength, not an objective measure. They are ordinal numbers: only the order of the numbers is meaningful, whereas the distance between two numbers

or grades does not lend itself to practical interpretation, and cannot be the basis for meaningful arithmetic operations (even though many publications quote non integer outcomes).

Having assessed the validity of approach of MRC grading of manual muscle testing (MMT), it is important to know if the method of assessment is reproducible. The inter-tester and intra-tester reliability of MMT graded with the MRC system has been shown to be acceptable (Hislop & Montgomery 2007). Another problem with this system is inherent inter-subject variability in muscle strength, this weakness makes it useful primarily for intra-subject changes in strength rather than inter-subject comparisons (James 2007). In addition, as James has pointed out “this system tempts the examiner to consider a muscle with a certain grade of strength as having the same degree of recovery as another muscle with the same grade, when in fact the amount of recovery necessary to enable the deltoid to be graded 3 may be considerably different than the amount of recovery necessary to enable a wrist extensor to be graded 3” (James 2007; MacAvoy & Green 2007).

It is now through necessary that if clinicians, in nerve surgery, are to pursue improvements in outcome for patients a scale more responsive to differences with in the MRC grade 4 range is required. This should be a continuous numerical scale where a force can be recorded as any value between 0 and the full power where there is an infinite range of possibilities between these two outcomes. This will then allow statistical comparison of differing populations to assess if any specific intervention has been beneficial.

With the advent of mechanical testing came the ability to measure muscle testing with accuracy using first mechanical and then more recently electronic means. The isokinetic dynamometer is a lab based device which offers a very high reliability and validity for a variety of bio-mechanical assessments. Isokinetic dynamometers, such as the Cybex (USA) (Rowell 1988), the Biodex (USA) (Valovich-McLeod et al. 2004), or the model D60107MK1 Penny and Giles transducers Christchurch, Hampshire) (Quick et al. 2016) [Chapter six] can measure number of properties such as dynamic peak torque, peak torque angle, angle-specific torque, power, and energy used. Their use is, however, not applicable in the standard clinic environment and thus their utility is limited.

Thus the hand held dynamometer was developed and with techniques to maximise its reproducibility and reliability. The assessment of force with a hand held dynamometer have historically been shown to be valid in both adults and children (Bohannon 1995; Bohannon 1997).

Standard hand held dynamometers (HHD) can be used for the maximum volitional contraction (MVC) assessment they are practical and inexpensive.

*“We conclude that a hand-held dynamometer and a fixed dynamometer yield comparable results in patients with neuromuscular disease, provided that testing is limited to muscle groups producing relatively low forces”* (Brinkmann 1994)

Reproducibility studies have shown a high intra-class correlation coefficient (0.91–0.97) and low SEm (standard error of measurement) (3%) in all muscle regions tested (Colombo et al. 2000) showing intra-class correlation coefficient of 0.96 for elbow flexion.

Kilmer (Kilmer et al. 1997) agrees with a very similar reliability finding and stating Hand Held Dynamometry ‘appears to be a reliable method to measure maximal isometric strength in persons with neurogenic weakness, and may be useful to quickly and objectively evaluate strength in the clinical setting’.

Wiles & Karni 1983 reporting the Queen’s Square experience states that

*“For most muscle and some peripheral nerve disorders it is change in strength which is the ultimate manifestation of improvement or deterioration in the underlying disease.”*  
(Wiles & Karni 1983)

This paper finds

*“In conclusion we find that several muscle groups in patients with peripheral neuromuscular disorders can be satisfactorily and reproducibly measured using the hand held myometer ...and suggest that the technique is highly appropriate for routine clinical application.”*

Stark et al (2011) after undertaking a large systematic review on the comparison of HDD with isokinetic dynamometer conclude-

*“Compared with isokinetic devices this instrument [HDD] can be regarded as a reliable and valid instrument for muscle strength assessment in a clinical setting.” (Stark et al. 2011)*

A frequently identified criticism of HDD is that when measuring subnormal strength in strong muscle groups it can be that these will exceed the strength of the tester and thus be under estimated (Visser et al. 2003). Whilst this may introduce an error in theoretical application; the muscle and the population under study will uncommonly overcome the examiner.

*“Perhaps World War II surgeons using early techniques of nerve repair were gratified to achieve grade 3 strength in a previously paralyzed muscle, and the differences between grades 3, 4, and 5 did not concern them, because this level of recovery was usually not attained”*

*“Modern techniques may achieve better results and engender higher expectations of a measurement system.”*

*“Unless HDD is widely adopted or until a better grading system is developed and well validated, the MRC will continue to be used.” James 2007*

The argument is clear for the need, validity and reproducibility of HDD for measuring muscle force. The aim now, necessarily, must progress to consider other aspects of muscle re-innervation recovery other than peak volitional force. The patient's experience is central to this exploration. The history of assessing outcomes has evolved from physician assessed to patient assessed outcomes. This has been driven by a so called revolution in health care (Relman 1991) which works towards outcome measures that have validity to talk to improvement across a wide spectrum of influence (Swiontkowski et al. 1999): quality of life (de Putter et al. 2014), satisfaction (Hamilton et

al. 2013), function (Hudak et al. 1996), right down to to specific object orientated outcomes (Waljee et al. 2014).

## **4.2 Summary**

The history of assessment of muscle function has been, almost without other focus, centred around the assessment of maximal volitional force. This focus has grown and developed over time until (in recognition of the flaws of a discrete system) the technologic advances have made continuous peak force assessment possible.

Recognising other features of motor recovery function will provide more detail in assessing outcomes and these methods will undoubtedly now become more and more the focus of assessing the outcomes of re-innervated muscle function.

## 5.

# A web based Delphi questionnaire to assess motor outcome assessment attitudes in a cohort of international experts.

### Introduction

The basis of designing outcome measures for any assessment of treatment to improve muscle function after nerve injury necessitates measures that are sensitive to change and a knowledge of what amount of change (of that measure) is identified as significant by the patient. It has been identified that *“heterogeneous selection and measurement of outcomes in clinical trials further impairs the ability to synthesise results across studies in systematic reviews”* (Clarke 2008). IN this manner ‘agreement towards the standardisation of outcomes for clinical trials has been proposed as a solution to the problems of inappropriate and non-uniform outcome selection’.

It is thus important to know what is the accepted standard and is what the attitudes are of experts in the field as to what measures could be undertaken to improve upon these standards.

### 5.1 Research Questions

- What is used in common practice to assess motor function?
  - What should the ideal clinical assessment of motor function look like?
  - From the discussion in modern outcomes science and clinical practice it appears it will likely have to be multifaceted and combine some aspect of subjective and objective assessment.
- What do leading clinicians think?

## 5.2 Aims

### The aims were to:

- Characterise what the current opinion regarding motor assessment was across a group of clinical nerve injury experts.
- Identify what assessment methods were used currently and what expert opinion regarded as the strengths and weakness of these current methods.
- Identify if any maximal force assessments use any other measurement tool *other* than MRC grade.
- Assess the experts' opinions on what an MCID for re-innervated elbow flexion force would be.
- Identify what the expectation were for outcomes in each experts' practice from an Oberlin transfer and how this relates to the literature.
- Identify which aspects beyond peak force were considered to be useful to assess and which are being collected.
- Assess the degree to which Patient related outcomes were being deployed and which ones.
- Attempt to gain consensus on what data should be collected in the future.

## 5.3 Objectives

1. Establish and contact a group of experts who would engage with a Delphi process.
2. Design and administer an online questionnaire to assess expert opinion.
3. Respond to the themes of the primary responses to further clarify the opinion of the panel to the future direction of motor assessment.



## 5.4 Methods

A set of questions was designed by the author to invite responses towards the aims of the study. A combination of direct yes/no, multiple choice, open ended answers and Likert questions were used. See below for list of questions.

A web based questionnaire was loaded with this questions and offered up to receive responses. (Figure 5.1 shows a screen grab of the on-line questionnaire)

Experts were identified by invitations being extended to all delegates at the 22<sup>nd</sup> Sunderland Society group meeting in Frankfurt, Germany (December 4-6 2016) and the Anglo-Scandinavian nerve injury and plexus meeting (Stockholm, Sweden May 19-20 2017). At each meeting the author delivered a presentation on the above material (and the findings of chapter six) at two international meetings (subsequent discussion within the group at the Sunderland meeting was transcribed and is attached as an appendix). The audience of international leading Attending Consultant surgeons and leading therapist were asked to fill in an online survey hosted on Google Docs – (Google corp. Mountain View, California, United States). Across both meetings there were 70 delegates (15 delegates in Sweden and 55 in Frankfurt). The questionnaire received 18 respondents all Attending/ Consultant surgeons from the US, Canada, Sweden, Netherlands, Finland, Norway, Germany, India, Scotland and England.

N=18 respondents engaged with the first round. The results are below in **5.5**. The second round method is detailed in **5.6**.

QUESTIONS RESPONSES 18

## Delphi exercise

a request for expert opinion from medical staff expert in the field of nerve injury treatment

**Email address \***

Valid email address

This form is collecting email addresses. [Change settings](#)

**Please enter your name**

Short answer text

**Do you routinely use the MRC (0-5) Muscle Power grading for muscle recovery after denervation/reinnervation?**

☐ Yes

☐ No

☐ Other...

**Figure 5.1:**

a screen grab from the Google forms data collection page

### The following questions were posed

**Q1.** Do you routinely use the MRC (0-5) Muscle Power grading for muscle recovery after denervation/reinnervation?

**Q2.** Do you find the MRC Grading system for force:

very useful

quite useful

just something I do as a matter of course

nearly no use

pointless

I only use it for research purposes

**Q3.** What percentage of your elbow flexor restoration nerve transfers do you think attain MRC grade 4?

**Q4.** What percentage attain less than MRC Grade 4? (0-3)

**Q5.** What percentage of the outcomes do you think you would grade MRC Grade 5?

**Q6.** What other methods of assessing muscle power do you use routinely?

**Q7.** What force of elbow flexion (on average) do you think your patients attain from an Oberlin nerve transfer?

<1kg Force	5Kg Force	10Kg Force
1Kg Force	6Kg Force	11Kg Force
2Kg Force	7Kg Force	12Kg Force
3Kg Force	8Kg Force	13Kg Force
4Kg Force	9Kg Force	14Kg Force
		15Kg Force
		> 15Kg Force

**Q8.** What percentage do you think this in relation to the normal side?

**Q9.** Given a population of Oberlin transfers which has a mean Force of 7Kgs what do you think would be the necessary increase in force to be clinically relevant? (the Minimal Clinical Important Difference). As represented by difference to the right shifted red curve below.

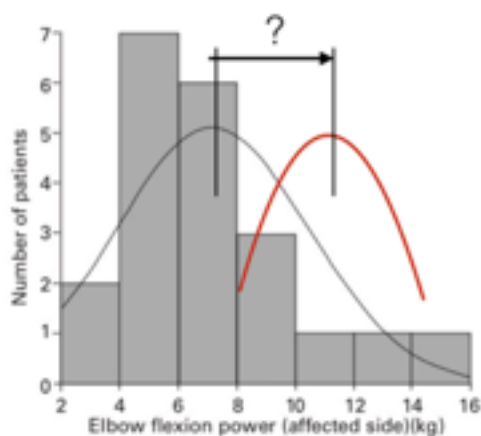


Fig. 1

**Q10.** Following on from this question what do you think the minimal assessable improvement in this cohort would be (the smallest difference we could reliably assess)?

**Q11.** Which of the following factors do you consider useful in assessing muscle recovery from denervation?

- select one, non or many of the following: maximal contractile force, sustainability of force, fatigability of effort, grade-ability of recruitment of force, control of other joints around the assessed muscle (e.g. shoulder ER when assessing elbow flexion), co-contraction, proprioception, pain, sensory alteration.

**Q12.** Do you find the results of any patient related outcomes (PROMs) useful in assessing your outcomes from nerve transfers? Yes/ no

**Q13.** If you do use PROMS - which ones? [Free text]

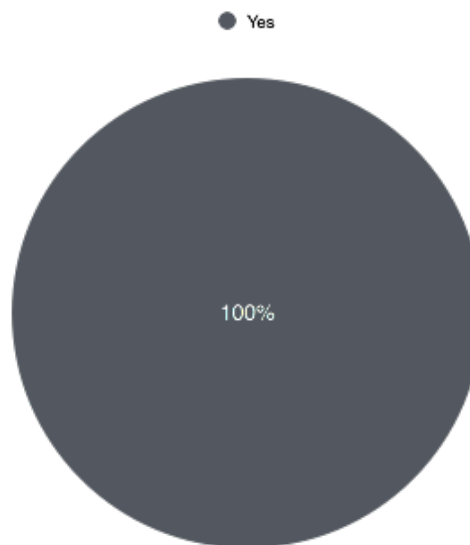
Following the first round the results were interpreted and the second round of questions was developed.

## 5.5 Results

The answers were as follows

**5.5.1 Q1.** Do you routinely use the MRC (0-5) Muscle Power grading for muscle recovery after denervation/reinnervation? (18 responses)

**A1.** 100% yes.



**Figure 5.2:**

Pie chart of responses to question 1

“Do you routinely use the MRC (05) Muscle power grading for muscle recovery after denervation/re-innervation?”

The use of the MRC muscle grading system is universal across all the clinics and countries sampled. This (as discussed in chapter four) is a situation which is well understood by clinicians, it has become the universal method applied in clinical discussions and published literature. It is a well used tool where by its weaknesses are well known but it is still favoured despite these; it has stood the test of time. Its longevity universality has made it part of the lexicon of motor assessment however it is this dominance that, it could be argued, is holding back development of novel tools of assessment.

**5.5.2 Q2.** Do you find the MRC Grading system for power (18 responses).

**A2.** Very useful (3) 17%

Quite useful (11) 61 %

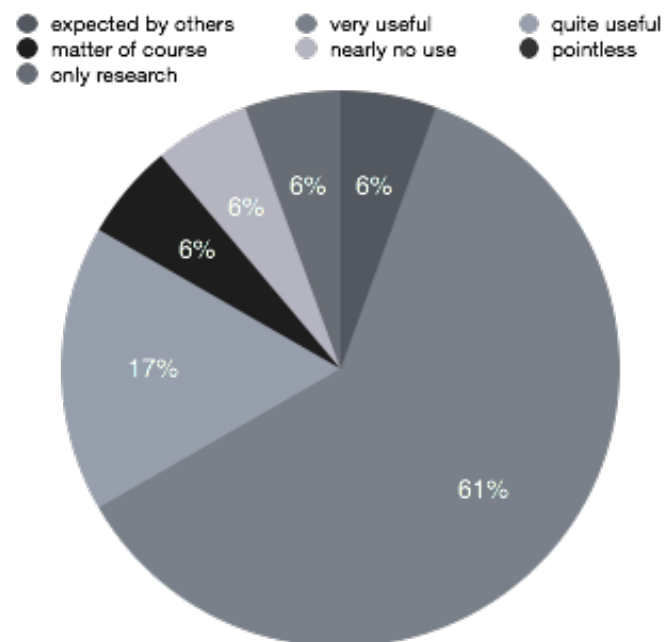
Just something I do as a matter of course (1) 5%

Nearly no use (1) 5%

I only use it for research purposes (1) 5%

Other (1) 5%

*“Expected by others, gives an impression easily understood by other doctors, but woefully unrelated to holistic function and heavily skewed towards minor increases in non-functionally relevant strength”*

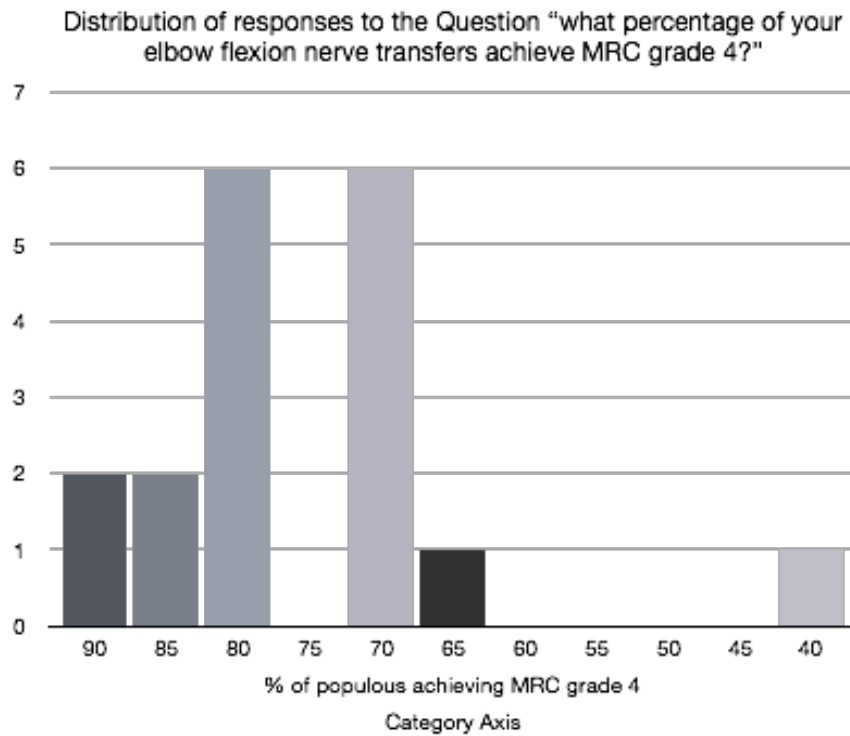


**Figure 5.3:**

Pie chart of responses to question 2 “. Do you find the MRC Grading system for power:”

**5.5.3 Q3.**What percentage of your elbow flexor restoration nerve transfers do you think attain MRC grade 4?(18 responses)

<b>% attain MRC Grade 4</b>	<b>90</b>	<b>85</b>	<b>80</b>	<b>75</b>	<b>70</b>	<b>65</b>	<b>60</b>	<b>55</b>	<b>50</b>	<b>45</b>	<b>40</b>
<b>Re- sponses</b>	<b>2</b>	<b>2</b>	<b>6</b>	<b>0</b>	<b>6</b>	<b>1</b>	<b>0</b>	<b>0</b>	<b>0</b>	<b>0</b>	<b>1</b>



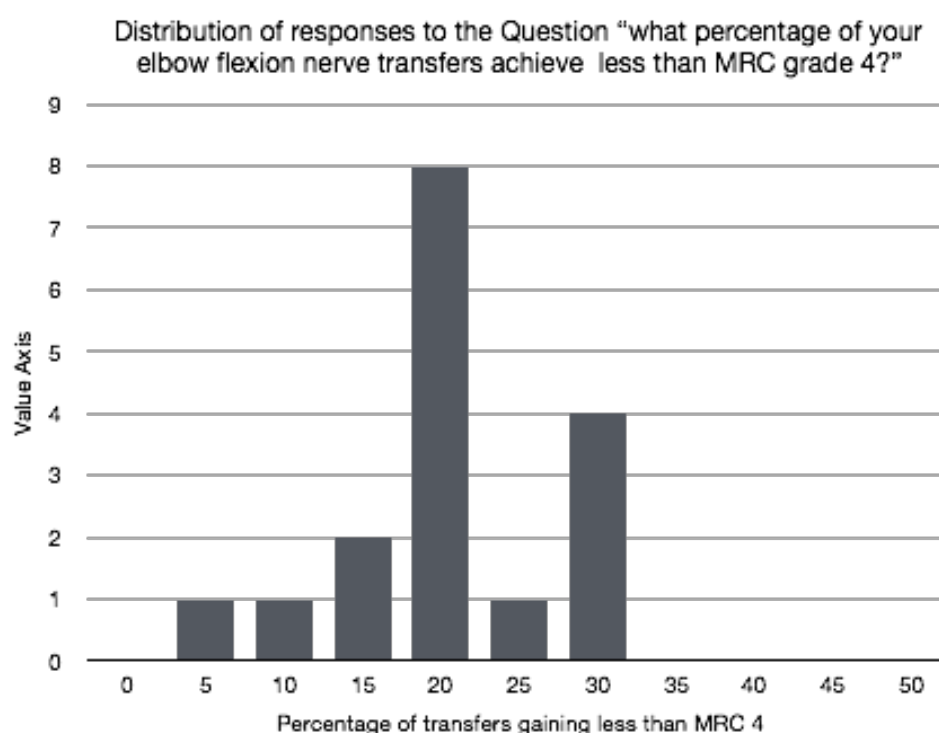
**Figure 5.4 :**

Histogram chart of responses to question 3 ".What percentage of your elbow flexor restoration nerve transfers do you think attain MRC grade 4?"

Thus 2/3rds of respondents believe over 80% of nerve transfers restore elbow flexion to MRC grade 4 and 89% believe over 70% of their case regain this level.

#### 5.5.4 Q4. What percentage attain less than MRC Grade 4? (0-3) (9 responses)

% attain > than MRC Grade 4	0	5	10	15	20	25	30	35	40	45	50	55	60
Re- sponses	0	1	1	2	8	1	4	0	0	0	0	0	1



**Figure 5.5:**

Histogram chart of responses to question 4 "What percentage attain less than MRC Grade 4? (0-3)"

This is not the exact inverse that one would have expected from question three. It does show that the range of opinion is between 15-30 percent of nerve transfers that do not attain MRC grade IV (the ability to lift weight against gravity).

#### 5.5.5 Q5. What percentage of the outcomes do you think you would grade MRC Grade 5? (9 responses).



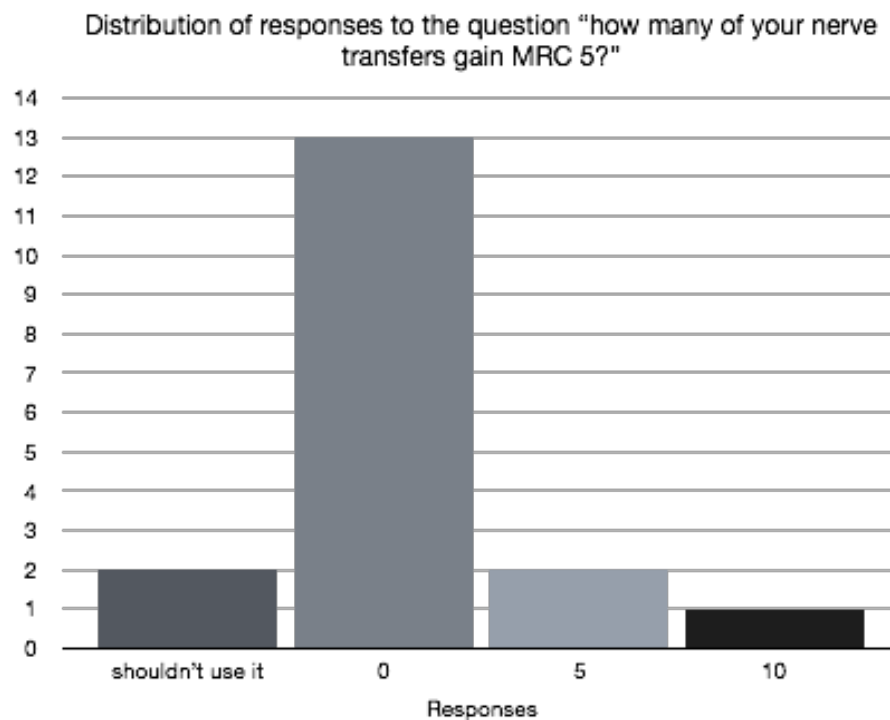
**A5.**

0% (13) 72%

shouldn't use it (1) 5%

5% (2) 11%

10% (1) 5%



**Figure 5.6 :**

Bar chart of responses to question Q5. "What percentage of the outcomes do you think you would grade MRC Grade 5?"

Over 2/3rds of experts are of the thought that re-innervated muscle never gains MRC grade V (normal) peak force and a further respondent was of the opinion that MRC V should not be (on principle of definition) assigned to a re-innervated muscle.

If we were to define 'normality' to be 2SD beyond the mean this would mean from our figures (normal arms 20.65KgF SD6.85) then normal could be defined as attaining 7KgF and below but

it is clear that even though our respondents recognise that (Q7) a mean outcome for this population is over this (7.11KgF) they do not consider this to be gradable as normal and thus perhaps are subconsciously considering other aspects of a muscle's function when they consider no one will attain a Grade 5 MRC ('normal'). This thought is highlighted by one respondent; who states that it 'should not' be used, by which, the author presumes, they mean that even though peak power may reach a level considered in the range of normal, the recovery should not be labelled as normal for other reasons.

#### **5.5.6 Q6. What other methods of assessing muscle power do you use routinely?**

**(15 responses- including multiple responses to this question).**

Pinch (2)

Dynamometer (5)

Calibration by weight lifted (discrete functional assessments) (5)

Grip (3)

Assessment of functional tasks (3)

Pinch (2)

Calibration by weight lifted in adults particularly (1)

Active range of movement (1)

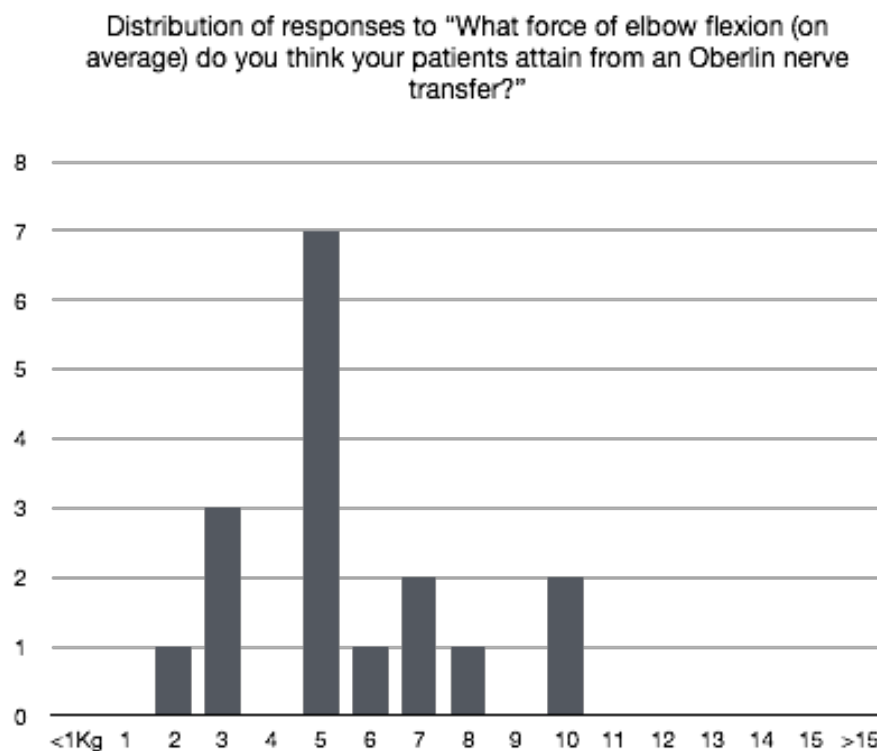
Verbal assessment of fatigue (2)

There were numerous other assessments of peak force; pinch, grip, calibration by weights lifted and dynamometer. These are all continuous measurements of force (other than weights lifted- a

discrete method of measurement). Only 3 respondents assessed any other feature of muscle function (2 cast a vote for: verbal assessment of fatigue and 1 for: active range).

**5.5.7 Q7. What force of elbow flexion (on average) do you think your patients attain from an Oberlin nerve transfer? (17 responses).**

**A7.**



**Figure 5.7 :**

Bar chart of responses to question Q7. "What force of elbow flexion (on average) do you think your patients attain from an Oberlin nerve?"

The mode response is 5Kg (mean for the distribution of these responses is 7.11KgF range 2-10).

### 5.5.8 Q8. What percentage do you think this in relation to the normal side?

(17responses) 1 answer – ‘no clue’.

Percentage of normal side	<10	10	20	30	40	50	60	70	80	90	100
Responses	1	0	0	8	3	4	0	0	0	0	0

A8.

The mean here is 23% mode 20% of normal force. Thus extrapolated from the force that the respondents gave as presumed mean (7.11KgF) this would give an estimate of the expected normal mean of 30KgF.

### 5.5.9 Q9. Given a population of Oberlin transfers which has a mean Force of 7Kgs what do you think would be the necessary increase in force to be clinically relevant? (the Minimal Clinical Important Difference) (13 responses).

A9

MCID (KgF)	0.5	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Re-sponses	1	1	5	0	0	2	0	1	0	0	1	0	0	1	0	0

The author recognises the low rate of response to this questions (13/18). The question may be poorly worded or the concept a difficult one but the concept was defined in the lecture given by the author to each of the invited audiences.

These responses give a median response for MCID of 3.57KgF and mode response of 2Kg.

Given the group defined the mean of outcomes as 7.11Kgs this is an MCID of 50%, taking the mode (2kgs) this is MCID of 29%.

**5.5.10 Q10. Following on from this question what do you think the minimal assessable improvement (MAI) in this cohort would be (the smallest difference we could reliably assess)?**

**(15 responses) of these 2 stated do not know.**

A10.

MAI	0.5	1	2	3	4	5	6
Responses	5	5	1	1	0	1	0

Thus the range of expected MAI is 0.96Kgs with our respondents presuming an average mean outcome of 7.11KgF MAD being 14% of the mean.

**5.5.11 Q11. Which of the following factors do you consider useful in assessing muscle recovery from denervation (18 responses)?**

**A11.**

maximal contractile force (9)

sustainability/ fatigability of force (5)

proprioception (1)

grade-ability of recruitment of force (0)

control of other joints around the assessed joint (0)

sensory alteration (0)

pain (0)

co-contraction (0)

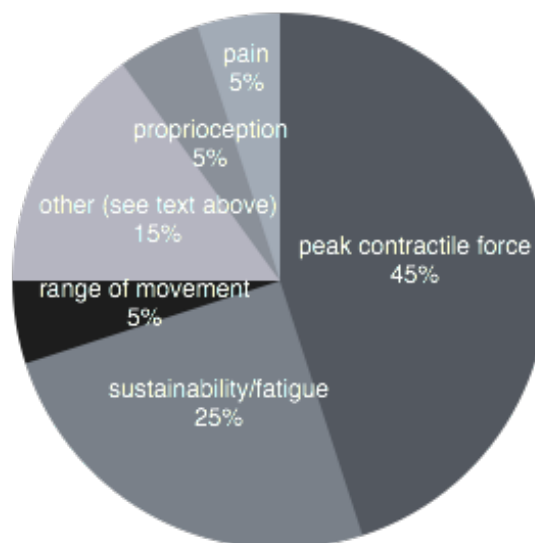
other (3)

*“All of the above, but the link only permits selection of one. The relative significance of each varies between muscle/joint movements” (1)*

*“Range of movement, force, co-contraction “(1)*

*“Most of the above” (1)*

Which of the following factors do you consider useful  
in assessing muscle recovery from denervation?  
n=18



**Figure 5.8 :**

Bar chart of responses to question Q11. “Which if the following factors do you consider useful in assessing muscle recovery from denervation?”

The responses show that 50% consider the assessment of maximal contractile force being useful. Sustainability has been rated as useful by 22% of respondents. The free text answers give further insight that a multifaceted assessment is most useful.

There is an appreciation of need for a more global assessment of re-innervated muscle function. Factors such as fatigue and the ability to maintain contractile force, control the joints and effect proprioception are important as well as the standard assessment of maximal volitional force.

**5.5.12 Q12. Do you find the results of any patient related outcomes (PROMs) useful in assessing your outcomes from nerve transfers? (14 responses)**

A12.

Yes 11

No 0

Other (3)

*"Unfortunately we don't use it routinely, but YES".*

*"Probably should use"*

*"Yes, but we do not use it."*

**5.5.13 Q13. If you do use PROMS (patient related outcomes) - which ones? (11 respondents some with multiple responses)**

A13.

DASH (6)

Psychology (2)

Quick Dash (1)

ADL's (1)

SF36 (2)

Michigan Hand (1)

PROMs (1)

PROMs often assess function or quality of life.

The Dash (The Disabilities of the Arm, Shoulder and Hand (DASH) Score is a validated study (Hudak et al. 1996) of upper limb function and is utilised widely for a functional assessment of upper limb global activity and is mentioned by  $\frac{3}{4}$  of those who responded that they had identified PROM outcome measures to use.

The short form 36 was developed as a global assessment of quality of life. It is validated in the UK populous (Hudak et al. 1996) and around the world. It assesses physical and mental well being and function.

**5.5.14 Q14. Thank you for your support in this project. Do you have any further comment to make?**

**(5 response)**

**A14.**

*“Laudable intention, very complex topic though.”*

*“MRC grade 5 represents normal power. This is never achieved after nerve repair.”*



*“We currently do not use PROMS on this population, but we are searching for PROMS that could be relevant for these patients. On obstetric brachial plexus palsy patients, we use Brief pain inventory, and plan to get the BPOM translated to Norwegian. We also plan to use the EQ-5D on the obstetric population.”*

*“Fatigability of effort is almost as important as maximal contractile force.”*

*“Difficult questions Tom. We do not have the answers to all your questions but have tried to fill in the boxes as good as possible.”*

#### **5.5.15 First stage conclusions:**

- This body of peers, active in the field of nerve injury treatment, demonstrate the spread of opinion around motor outcomes from nerve transfer.
- They demonstrate that there has been widespread acceptance of the method of assessing maximal volition force as a motor outcome.
- MRC grade is used universally however it is only considered very useful by 17%, the majority (61%) consider it quite useful and some consider it of little use.
- Assessment of force within MRC grade 4 is used by 11/18 of the group. With 5/18 using a continuous assessment of force (HHD) and 6/18 using discrete weights.
- The group considers that the mean expected outcome from an Oberlin nerve transfer is 7.11KgF which they consider would as a mean represent 23% of normal.

This data shows that the Delphi group considers maximal volitional force (MVF) as an entry level motor assessment. Perhaps best considered as a threshold assessment in recovery and that following the ability to attain some useful level of force other features should be assessed along with it. (It makes no sense to assess sustainability if there is no force to sustain and no point in

assessing features of a function which has no application). To further characterise the agreement on the relative importance of these differing recognised aspects of re-innervated motor pattern further questions were asked of the group.

## **5.6 Second stage method**

The same clinicians, that responded to the first round, were contacted again by email. They were thanked for their engagement and given the raw anonymised data of the first round findings. They were again asked to complete an online questionnaire; The following questions were designed by the author to identify the group's opinion on best practice.

### **Second round Questions:**

**Do you agree to the following statements (1 - not at all to 5 - completely agree).**

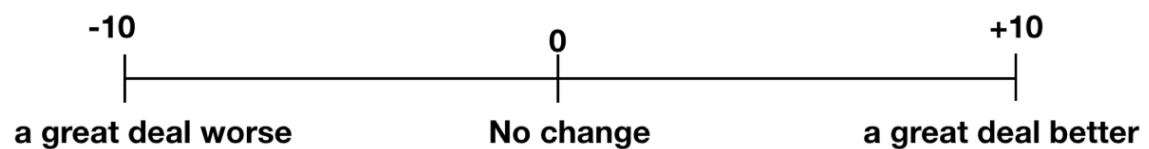
- **Peak force assessment is an essential part of assessing re-innervated muscle function**
- **An assessment of fatigability would be useful as part of assessing re-innervated muscle function**
- **An assessment of grade-ability of recruitment of force would be useful as part of assessing re-innervated muscle function**
- **An assessment of muscular pain would be useful as part of assessing re-innervated muscle function**
- **An assessment of afferent (proprioception, muscle pinned function, etc) function would be useful as part of assessing re-innervated muscle function**
- **As a global patient-reported outcome (PRO) would you consider PGIC (see below) would be useful as part of assessing the outcome of a nerve transfer.**

**Patient related global impression of change (PGIC) is a simple assessment where-by (at a set time) post operatively the patient is asked what their impression of change from that operation has been:**

### **Patient's Global Impression of Change (PGIC)**

please mark a point on this line to show

**What difference has there been since your surgery ?**



The above questions were again presented via Google forms online.

## **5.7 Second round data**

From the invited group of 18, n=10 second round answers were received.

They were as follows.

**5.7.1 Q1. Peak force assessment is an essential part of assessing re-innervated muscle function (1-not at all to 5- completely agree)**

Score	1	2	3	4	5
# of re-sponses	0	0	2	4	4

**Score 4.2/5**

There is agreement to strong agreement here (with no disagreement)- Peak force is considered an essential part of assessing re-innervated muscle function.

**5.7.2 Q2. An assessment of fatigue-ability would be useful as part of assessing re-innervated muscle function (1-not at all to 5- completely agree)**

Score	1	2	3	4	5
# of re-sponses	0	0	0	5	5

**Score 4.5/5**

Greater agreement here with a tighter spread. All respondents either 4/5 or 5/5 agreed that an assessment of fatigability would be a useful part of assessing re-innervated muscle function.

**5.7.3 Q3. An assessment of grade-ability of recruitment of force would be useful as part of assessing re-innervated muscle function (1-not at all to 5- completely agree)**

Score	1	2	3	4	5
# of re-sponses	0	0	4	4	2

**Score 3.8/5**

Agreement, but less strong than for peak force and fatigue seen for assessing grade-ability of recruitment of force.

**5.7.4 Q4. An assessment of muscular pain would be useful as part of assessing re-innervated muscle function (1-not at all to 5- completely agree)**

Score	1	2	3	4	5
# of re-sponses	0	4	3	3	0

**Score 2.9/5**

A balance of mild agreement and disagreement here for muscular pain being useful.

**5.7.5 Q5. An assessment of afferent (proprioception, muscle pinned function, etc) function would be useful as part of assessing re-innervated muscle function**

Score	1	2	3	4	5
# of re-sponses	0	3	3	2	2

**Score 3.3/5**

**5.7.6 Q6. As a global Patient reported outcome (PRO) would you consider PGIC (see below) would be useful as part of assessing the outcome of a nerve transfer.**

Score	1	2	3	4	5
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<b># of re-sponses</b>	0	2	0	5	4
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**Score 4.4/5**

### **5.7.7 Summary**

Thus in rank order of agreement on what should make up an assessment of function of re-innervated muscle function:

Fatigue, Patient reported outcome, Peak Force all attained greater than 4/5 Likert agreement.

With assessment of recruitment, proprioception and pain being less than 4/5 agreement.

## **5.8 Discussion**

As part of this review of muscle function assessment a group of expert views were sampled from larger expert groups and questioned for their view on what and how motor function should be assessed following nerve transfers. Through the two stage Delphi there has been an attempt to come to a consensus on how to assess re-innervated muscle function. The Delphi technique is a widely used and accepted method for gathering data from respondents within their domain of expertise. The technique is designed as a group communication process which aims to achieve a convergence of opinion on a specific issue. Participants in a Delphi study do not interact directly with each other, so situations where the group is dominated by the views of certain individuals can be avoided.

Delphi groups have been used widely in clinical medicine and surgery to inform scoping exercises for research questions (Schneider 2016), gain consensus for treatment recommendations (Van Vliet et al 2016) and to identify which parameters to measure in clinical trials (Sinha 2011). There has been discussion (Powell 2003) of the merits and pitfalls of this method of harnessing

the opinions of an often diverse group of experts on practice-related problems. Particularly challenging is the level of evidence it is considered to provide inhabiting, as it does, the ground between opinion-based and evidence-based research (Powell 2003).

To place this work in nerve injury within the context of the current body of knowledge we reviewed the English literature using the search string “Dephi” AND “nerve injury” OR “nerve”; There were only two published full studies on nerve injury using a Delphi approach in clinical aspects of nerve injury. One poster reference was also identified.

Scmid & Coppieters 2011 invited 50 experts to discuss ‘double crush’ nerve pathology and garnered 17 responders of whom 16 complete their 3 stage process towards delineating the mechanism(s) underlying the pathology. In a Delphi study on sensory therapy Jerosch-Herold 2011 invited the opinions of 70 hand therapists and of the 10 responders, 7 responded to all three rounds. A poster presentation by Dy et al (Dy et al 2017) assessed which portions of a nerve decompression operation were deemed to be critical by a three stage Delphi with 10 respondents they did not explicitly identify the method used to identify the group nor did they characterise their experience.

The first round of this Delhi process demonstrated that the MRC grade was universally deployed [A1] to assess peak force and that this was the top outcome assessed [A6]. There is however a section of responders [A2] who see the MRC grade as insufficient or inadequate: only 17% rated the MRC grade very useful with 22% rating the score as not useful (“nearly no use”, “just something I do as a matter of course” or “woefully unrelated to holistic function”). Having exposed the lack of support for a wider utility for the MRC grade it is still true that of the factors considered useful in assessing motor function [A11] peak contractile force represents the majority of responses (50%). Thus the author assesses that the Delphi group whilst deeming peak force important see MRC grade assessment as inadequate for this role. The validity and utility of a continuous measure of force in motor assessment has been supported widely in the literature [Quick 2016]. This is shown [A6] in the current support for continuous measurements of force (pinch measurement, dynamometry, grip assessment).

Moving assessment beyond that of peak force; there is a wider appreciation of motor assessment apparent [A11] with sustainability of force, fatigue, proprioception and range of movement all featuring in responses. There were no positive responses for grade-ability of force being a useful aspect of assessment however.

Interestingly the Delphi group strongly favour assessment of the efferent functions of re-innervated muscle – the only afferent assessment selected, as being potentially useful in clinical assessment, is that of proprioception (with only one response). There were no respondents who selected pain or sensory alteration as important. Contrast this with the findings from the data on the subjective patient experience in chapter nine. There is evidence of a disconnection here between the professionals' impression of what it is important to assess and the patients' voice on this matter.

Moving to subjective assessments and PROMs, following the increasing popularity of such methods worldwide (Weldring & Smith 2011) the Delphi group showed that these were used by 14 of the respondents (all of those that replied to Q13). Of these, two used a quality of life outcome (QoL) the Short form 36 (SF36). The others used functional assessments. The Disability of the arm shoulder and hand (DASH) or a validated shortened version of this. One stated they deployed an assessment of activities of daily living (ADL). This was an area where 90% (n=9/10) of respondents in round 2 agreed to a Likert level of 4/5 or 5/5 that a specific subjective outcome of change (PGIC) assessment would be useful.

The second round again demonstrated the importance to the expert group of peak force with 80% agreeing 4/5 or 5/5 that it is an essential part of assessment of a re-innervated muscle. 100% agreed (at a 4 or 5/5 level) that an assessment of fatigue-ability would be useful as part of assessing re-innervated muscle function. Grade-ability of function as an important outcome attracted only 60% agreeing 4 or 5/5 (the others showing neither agreement nor disagreement). On muscular pain assessment there was even less support (30% with 4 or 5/5) with 40% disagreeing. Support was at similar proportions for assessing the afferent pathways.



This is novel data and there is no specific literature with which to compare it. It is shown however that this sample of international experts sees that peak force should be seen as part (and not the part of the assessment which met with most agreement on its importance either) of clinical studies on this area of muscle re-innervation. Historically such studies have focused on peak force to the exclusion of any other assessment (Figure 7.9).

## **5.8 Limitations**

A significant limitation of this study is the potential for selection bias: The specialists were approached to engaged via two international meetings the catchment was over 70 such specialists. The Delphi group we questioned was made up of 18 respondees; self-selected from from a larger group to whom the invited was extended. Groups of this size are however common in Delphi processes. Murphy et al (1998) reports that reliability is compromised by fewer than six participants, whereas groups in excess of 12 do not increase reliability of judgments thus the sample size itself is not in question but the method of selection is open to bias. The concern therefore is posseted that the responses may not be representative of the larger community. The author intends to mitigate this assertion by publishing these data for peer review and to prompt wider discussion. The group was noted to be internationally heterogeneous with responses from across a number of differing countries. There is implicit response bias in a group like this but to recruit those not engaged in this area would lead to a low response rate. Even this self selecting group shows a drop off between stage one and two (18-10). It could however be considered; that given the open invite, the Delphi group were a self selecting group of those interested and engaged with the subject of motor assessment (the free comments support this assertion) and thus not representative of the wider community. It is not possible to assess how the sample size and drop off has influenced the results and the intention to publish the work for wider consumption and discussion will inform this and allow future projects to benefit from this input. There is no other literature regarding the consensus in this area that this data will attract interest and comment.

The assumptions the author draws regarding the pervading practice across those in practice are valid only if the practice of the experts is seen to be representative of that of their peers. The utility of a Delphi process allows opinion to be canvassed. The validity of using such a process to survey practice may not hold as individual practices (rather than the underlying intellectual process or reasoning which Delphi process were set up survey), may have regional reasons why they do not align. A formal site by site survey would be the most appropriate manner to establish the practices in use but would be impractical to establish in any manner other than a process similar to this. The questions though would be posed as a survey of clinic site or unit practice rather than a question on individual practice.

## **5.8 Conclusions**

As set out in the aims; this study has demonstrated the opinions of working expert clinicians in the field on the subject of re-innervated muscle assessment.

Maximal volitional force remains the clinicians' primary outcome measure. The assessment methods used currently are mainly the MRC grade. The current state of muscle re-innervation assessment is that MRC grades of force are used as the universal outcome measure. Although most recognise this has shortfalls (with only 17% grading as a very useful tool).

Experts expect 7.1KgF peak force from their Oberlin transfers; This is representative of what the published literature states. (Bhandari 2011, Carlsen 2011, Martins 2013, Quick 2016).

There has been some consensus reached through this process on what data should be collected in the future, peak force is considered to be one of the most important reported outcome but there is a recognition that fatigue and patient related outcomes should form part of any assessment.

## 6.

# A quantitative assessment of the functional recovery through nerve transfer reconstruction of elbow flexion in patients with a brachial plexus injury

Published after registration as:

TJ Quick, AK Singh, M Fox, M Sinisi, A MacQuillan. Bone Joint J 2016;98-B:1517-20<sup>3</sup>

### 6.1 Abstract

Introduction: Assessment of the efferent function of motor function is essential both to assessing the outcome of nerve injury treatment but also to inform research towards a better understanding of muscle re-innervation (to allow development of better treatments). The current standard is to assess the peak contractile force via the Medical Research Council (MRC) assessment. The MRC assessment is applied universally by experts in the field (chapter five), with 83% of these considering it is less than very useful. As a discrete, rank assessment tool the MRC force assessment does not provide sufficient information to fulfil all of these roles. This study set out to use a continuous measure of recovered muscle force to characterise a population of patients who had undergone nerve transfer. The intention is that such a population of

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<sup>3</sup> Published paper included as an appendix, inclusion of an amended text is made with the full agreement of all authors, who's contributions were; support of data collection (A Singh) and comments on the final text (M Fox, M Sinisi, A MacQuillan). The concept, justification, design and delivery of the study were the authors own work.

nerve transfer re-innervated elbow flexion function patients may form the basis of future study as a research population (chapter four, chapter ten).

Methods: Twenty-six patients (range 16-66 years) from a cohort of fifty-two eligible patients attended review examination. Inclusion criteria were that the patient was at a point greater than two years after having undergone a nerve transfer procedure for elbow flexion, between 2006-2012. Their elbow flexion strength outcome was measured in a clinical outpatient environment with a static dynamometer.

Results: These data showed 81% of nerve transfers gained elbow flexion strength of MRC grade 4 and would by standard assessment thus all be indiscernible by traditional assessment (chapter 3,4). We examined the spread of results within the MRC range and showed the average force outcome was 7.2Kgf (range 3-15.5Kgf), standard deviation of 3.3 and variance 10.8.

Conclusion: This study establishes the dynamometer as a viable tool for assessing peak force outcomes following elbow re-innervation in a standard clinical set-up. It is suggested, as the HHD equipment is inexpensive that this method should be widely adopted to further inform the traditional MRC grade attained in around 80% of patients in outcome studies of re-innervated muscle.

## **6.2 Introduction**

Brachial Plexus injuries are a rare (Midha 1996) and severely debilitating condition. The majority of cases are young men involved in motorbike accidents (Midha 1996). This injury results in physical disability, psychological distress and also has significant socioeconomic implications; A significant proportion of patients are not able to make a return to their previous level of activity (Choi 1997). There has been over the past few decades an increase in knowledge and understanding of the pathology and physiology following nerve injury through basic science and animal experimentation. This knowledge base has driven a change in approach in dealing with

nerve injuries, and changed it from 'wait and watch' to more aggressive approach of 'early intervention'. This evolution of treatment is still clinically contentious but has a growing evidence base demonstrating improved outcomes, in terms of global functionality and quality of life (Kretschmer et al. 2009, Bengtson et al. 2008, Kato 2006, Leechavengvongs et al. 1998, Htut et al. 2016, Oberlin et al. 1994, Teboul, Kakkar, Ameer, Beaulieu, et al. 2004, Tung et al. 2004). It is the intention of this paper to support this move. Demonstrating that more adept, sensitive and scientific outcome measures will allow study not just of the model used in this paper but all other motor outcomes.

Surgical intervention such as nerve repair and/or nerve transfer gives the best chance for regaining maximum function after severe brachial plexus injuries (Kretschmer et al. 2009, Bengtson et al. 2008, Kato 2006, Leechavengvongs et al. 1998, Htut et al. 2016, Oberlin et al. 1994, Teboul, Kakkar, Ameer, Beaulieu, et al. 2004, Tung et al. 2004). One of the aims of surgical planning in this situation is restoration of elbow flexion (Htut et al. 2016, Oberlin et al. 1994, Teboul, Kakkar, Ameer, Beaulieu, et al. 2004, Tung et al. 2004, Carlsen et al. 2009, Shin et al. 2005). Carlsen (2011) showed that in the laboratory setting it is possible to apply the use of a hand held dynamometer (HHD) to assess peak contractile force, in order to popularise this approach it is necessary to demonstrate its efficacy in the clinical environment.

The era of proof of concept of nerve transfers has now passed; it now falls to this generation to improve upon the work of those before us. In order to assess an improvement in outcomes it is (after clear criticism of discrete measures of force) now necessary to adopt a continuous scale to measure the range of force created by the re-innervation procedure. Through this approach it will be possible to demonstrate small differences and thus to finesse surgical technique and to use this controlled model (chapter four) as a method of study of nerve regeneration.

## **6.3 Aims & Objectives**

### **6.3.1 Aims:**

1. Characterise and describe (mean, SD) the population of peak force outcomes using KgF
2. Popularise the utility and validity of HHD assessment of force in assessing re-innervated muscle.
3. This data will inform planned future studies into improving nerve regeneration outcomes.

### **6.3.2 Objectives:**

1. Identify a Cohort of Oberlin transfer patients with documented MRC grade 4 recovery of elbow flexion greater than 2 years post operation.
2. Utilise this population to study the peak force generated with maximal effort.
3. Assess this force with a Hand held dynamometer to produce continuous data.

## **6.4 Material & Methods**

### **6.4.1. Data Collection**

The project was approved after institutional PEP (project evaluation review process) and REC (Research Ethical Committee) approval. A retrospective review of the RNOH's peripheral nerve injury unit's database was performed. Patients were included who underwent nerve transfer for returning elbow flexion from May 2006 to May 2012 and had a follow-up of at least 2 years post-procedure. Fifty-two such patients who had ulnar and median nerve fascicle transferred to biceps (+/- brachialis) were identified, and they were invited to a follow-up clinic. Twenty-six patients attended the follow up appointment. The low percentage is typical of other follow up

studies in trauma series and may also reflect the wide geographic (national) referral base of the clinical unit with long distances perhaps also contributing to an unwillingness to return to be assessed at 2 years or greater post intervention.

A dynamometer (model D60107MK1 Penny and Giles Transducers, Christchurch, Hampshire) was used for measuring quantitatively the strength in re-innervated biceps (Fig 6.1). The instrument was calibrated at the RNOH Biomechanical Institute. Patients were seated on a chair, with the elbow flexed at right angle and forearm rested on the table. The force plate of the dynamometer was placed at a fixed point, 10 cm proximal to distal wrist crease, and the examiner applied a force to maintain an isometric contraction of the subject. The effort was maintained for 3 seconds with strong verbal encouragement and the peak force was recorded. The readings, which were in Kilogram force (KgF), were recorded in three different positions, namely in full forearm supination, neutral and full pronation. (Figure 6.2)



**Figure 6.1:**

Hand held dynamometer (model D60107MK1 Penny and Giles Transducers, Christchurch, Hampshire)

At the clinical research review, patients were assessed by a disinterested observer for returned elbow flexion force. The assessment was carried out in a standard clinic room with no specialist equipment other than the dynamometer. The measurement of elbow flexion was performed in three positions of forearm rotation (full supination, neutral and pronation). These measurements were repeated twice. These readings were then averaged, as it was observed that the patients varied in their strength in different forearm positions and sometimes could not attempt any elbow flexion in a particular position. The other arm was used as control. The regained strength of injured extremity in elbow flexion was compared to the contralateral side and expressed as a percentage.



**Figure 6.2:**

Hand held dynamometer in use with three differing positions of measurement.

Synchronous brachioradialis and or triceps muscle activity during elbow flexion were clinically assessed with visual inspection and palpation. The clinical notes were reviewed to determine their documented historic progress, in terms of MRC grade, at six, twelve and twenty-four months follow-up.

Patients were seated on a chair, with the elbow bent at right angles and forearm resting on the table. The force plate of the dynamometer was placed at a specific, but arbitrary point, 10cms proximal to the distal wrist crease, and the examiner applied a resistive force through it. The force generated by the patient to overcome this resistance was noted. The readings were taken in three different positions, namely in forearm supination, neutral and pronation (Fig 6.2). There



were two observers who obtained two sets of readings on each individual patient. The other arm was used as a control.

#### **6.4.2 Patients**

Twenty-six patients and their case notes were reviewed for this study. During this assessment, patients were assessed for synchronous brachioradialis and triceps muscle activity during elbow flexion. There were twenty-three patients who had a single and three who had a double transfer.

#### **6.4.3 Study Demographics**

The group studied was made up of twenty three male and three female patients, with a mean age at the time of operation of 37.3 years (16 to 66). Their median time between the index injury and the Oberlin procedure was 18.7 weeks (one day to 64.1 weeks). A total of 21 patients underwent quantitative assessment for the strength of their re-innervated biceps muscle as they had attained the ability to flex the elbow against resistance.

#### **6.4.4 Injury Demographics**

There were fifteen patients with left-sided and eleven with right-sided brachial plexus injuries. Of these, twelve were on the dominant side and fourteen on the non-dominant side. A total of twenty four had sustained the injury in a road traffic incident, of whom seventeen were riding a motorcycle. One patient sustained an injury playing rugby, and one had an iatrogenic injury at the time of an intrascalene block. The strength of elbow flexion improved gradually post-operatively with the first flickering movement noticed at around six months.

#### **6.4.5 Statistical Analysis**

Statistical analysis was performed using SPSS software package (version19). A two-tailed p-value was determined, for these two continuous data sets with statistical significance set at  $p < 0.05$ .

## **6.5 Results**

### **6.5.1 Force outcome**

At a mean follow-up of 56 months (28 to 101) the mean strength of flexion of the elbow was 7.2 Kgf (3 to 15.5; SD 3.3). When compared with the contralateral arm was a mean of 34.7% (median 33%, interquartile range 11.9% to 66.5%). Figure 6.2 shows the values for the strength of flexion of the elbow obtained for the group with MRC grade 4. Eighty percent of this cohort (21/26) undergoing nerve transfer gained MRC grade 4 strength of flexion. Within this group of twenty-one cases the spread of data within the grade MRC 4 was a mean of 7.2 Kgf (3 to 15.5; SD 3.3). This equates to between one-eighth to two-thirds increase in strength, and an average of up to one-third of normal.

Number	Pt.	Age @ Injury (years)	Injury Level	Donor nerve	Recipient nerve	MRC Grade	Peak readings on Affected side for each position (S/N/P) KgF	Mean reading -Affected side [(S+N+P)/3] KgF	Peak readings on Normal side for each position (S/N/P) KgF	Mean reading -Normal side [(S+N+P)/3] KgF	%Elbow Strength
1	SP	15	C5-6	U	B	4	17/9.6/8.5	11.7	22/19.9/17.3	19.7	59.4
2	DB	18	C5-6	U	B	4	11.9/9.3/7.9	9.7	21.1/17.8/19.8	19.6	49.2
3	BP	23	C5-6	M	B	4	4.0/3.3/6.5	4.6	26/21/28.7	25.2	18.3
4	TH	29	C5-6	M	B	4	6.5/6.1/7.2	6.6	18.6/20.6/20.8	20	33
5	KC	35	C5-6	U	B	4	5.8/8.1/6.3	6.7	23/17/24.7	21.6	31
6	MH	46	C5-6	M	B	4	7.9/6.2/7.9	7.3	17/23.8/16.1	19	38.4
7	SP	46	C5-6	U	B	4	5.4/5.3/6.6	5.8	28.2/31.1/22.9	27.4	21.2
8	CB	35	C5-6	U+M	B&B	4	4/2.8/7.2	4.7	22/18.5/18.5	19.7	23.9
9	SB	41	C5-6	M	B	4	8.4/3.1/6.4	6	21.1/21.4/22.8	21.8	27.5
10	IB	41	C5-6	U+M	B&B	4	8.9/7.2/7.7	7.9	19.8/15.1/14.5	16.5	47.8
11	CM	43	C5-6	U	B	3	Nil	Nil	28.1/22.4/17.5	22.7	Nil
12	DB	35	C5-6	M	B	3	Nil	Nil	19.2/17.5/ 18.3	18.3	Nil

13	BA	47	C5-6	U	B	1	Nil	Nil	16.3/20.2/16.5	17.7	Nil
14	SA	17	C5-6	U	B	4	4.8/2.2/3.5	3.5	18.2/12.9/11.2	14.1	24.1
15	NA	34	C5-6	U	B	4	12.7/5.4/10.5	9.4	18.2/20.5/20.6	19.8	47.5
16	SW	21	C5-6	U	B	4	12.2/13.2/14.7	13.4	28.5/29.5/25	27.7	48.4
17	RR	64	C6	U	B	4	4.8/5.0/5.1	5	11.8/10.8/11.2	11.3	44.2
18	AW	42	C5 -7	U	B	4	4.5/4.4/6.0	5	23.2/ 20.9/ 19.1	21	23.8
19	DC	30	C5 -7	U	B	4	8.2/ nil/ nil	8.2	20.1/27.5/25.4	24.3	33.7
20	LC	19	C5 -7	M	B	4	3.1/2.3/3.6	3	26.9/26.1/22.8	25.3	11.9
21	GM	44	C5 -7	U	B	4	4.0/3.0/5.6	4.2	19/14.2/19.8	17.7	23.7
22	PJ	41	C5 -7	U	B	4	3/4.9/5.3	4.4	22/21.2/19.3	20.8	21.1
23	FG	66	C5 -7	M	B	0	Nil	Nil	16.4/15.2/15.8	15.8	Nil
24	RA	52	C5 -7	U	B	3	Nil	Nil	17.6/ 18.2/ 17.1	17.6	Nil
25	KP	53	Infraclavicular	U	B&B	4	8.6/5.4/9.3	7.8	25.8/24/17	22.3	35
26	TB	33	Infraclavicular	U	B	4	16.9/15.4/14.2	15.5	26.3/22.0/21.4	23.3	66.5

Figure 6.2

Table summary of injury pattern and outcome following Oberlin procedure.

U: Ulnar, M: Median, B: Biceps, B&B: Biceps & Brachialis, S: Supination, N: Neutral, P: Pronation Taken from Quick et al 2016 with permission of all authors.

Synchronous contractions of brachioradialis were noted in every case during attempted elbow flexion. This was greatly reduced when elbow flexion was attempted in the position of full supination we were unable to quantify the contribution of this change. Triceps co-contraction were demonstrable in two cases.

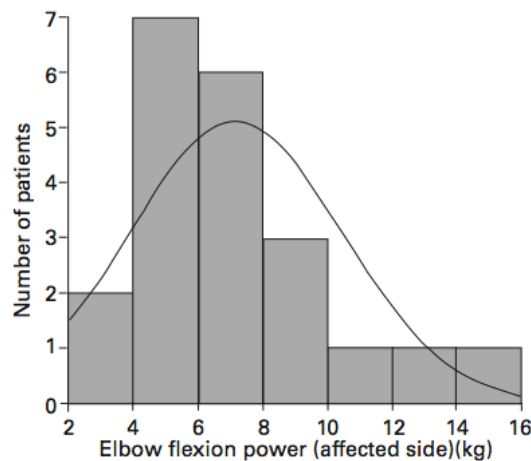


Fig. 1

Gaussian curve showing the distribution of Medical Records Council grade 4 power in the patients at mean follow-up of 56 months (28 to 101).

**Figure 6.3:**

Force curve depicting MRC Grade 4 subset distribution. Mean 7.2 KgF (3 to 15.5; SD 3.3).  
(Best fit line as calculated by SPSS software)

Thus it was observed that more than 80% of patients undergoing nerve transfer, will gain an elbow flexion strength of MRC grade 4, This is in keeping with other reported case series (figure 7.9 ) placing these data as commensurate with other groups. The strength of this study is to further assess this group of MRC 4 outcomes. Measuring they have, on average, recovered an elbow flexion power of 7.2 KgF equating to a force which is an average of one-third of the other arm's strength.

## 6.6 Discussion

The standard assessment of outcomes from nerve transfers have universally been expressed via MRC grade. The move from this technique has started to occur, driven first in this field by a discussion of how to discern a difference between differing surgical techniques for nerve transfer.. Carlsen (2011) presented his findings of a retrospective study using a sophisticated biomechanic laboratory set up, comparing (6) single versus (16) double nerve transfer.. The study was inadequately powered to show a difference. The data revealed elbow flexion strength was  $8.94 \pm 5.92$  Nm and  $12.54 \pm 11.76$  Nm respectively single and double (Carlsen et al. 2011). Martins (2013) followed this study with a slightly larger prospective cohort (18 single 19 double) over 5 years; Having performed a (one presumes a post hoc) power analysis and assessing 84 patients were necessary to show a difference he proceeded with a single surgeon single site study assessing his own outcomes and showing  $4.14 \pm 3.27$  KgF (single) and  $5.6 \pm 2.41$  KgF.

In this study, of the twenty-six patients twenty-one attained a MRC grade 4 power which when quantitatively assessed with the dynamometer showed mean elbow flexion strength of  $7.2 \pm 3.3$  kgF. This is close to the values  $8.94 \pm 5.92$  Nm, obtained in a biomechanical laboratory set-up by Carlsen (2011). Also, the mean percentage elbow strength compared to contralateral side in this study was  $34.7 \pm 14.4\%$ , again not hugely different from this study. The data does not allow us to perform any sensible comparison of these data (between single versus double nerve transfer) due to the significant difference in numbers between the groups (23 vs 3). This study was not designed to show any such difference. There were six cases in this study that underwent nerve transfer within two weeks of their injuries (after exploration and identification of avulsion lesions at the site of injury in the supraclavicular brachial plexus). These six cases all achieved a MRC grade 4 at a two year period

This is the first study looking at the medium term outcome; 2 years post procedure, for the UK population. This study presents an example of how in a practical manner a continuous quantitative measurement for regained elbow strength can be carried out in a standard clinical environment and it is hoped the data and descriptive technique will popularise the use of HHD in assessing continuous peak force assessment. Such a process allows the clinician and patient to compare the reading from previous follow-ups to record recovery increasing engagement with rehabilitation. It also avoids the use of the epithetic MRC descriptors 4-, 4+, 4++ which are not validated sensitive or reactive measures. The values obtained during this assessment are similar to those obtained under biomechanical laboratory conditions (Carlsen 2011). This supports and validates the feasibility of use of HHD as a measurement tool in clinics in future.

The following limitation of the study design are acknowledged: Elbow flexion peak force should have ideally been measured as a torque (Nm as in Carlsen 2001) this would have required a calculation of how force was applied across a moment arm formed by the distance between the centre of rotation of the elbow (the trans-epicondylar axis) and the centre of gravity of forearm (where the resistance was applied) which would be different in each arm (due to variation in the mass distribution within the forearm). This is only possible in a formal biomechanical laboratory (as assessed in Carlsen 2011). The use of KgF was therefore the only possible assessment and was undertaken to demonstrate that this technique can be widely applied in a standard clinical setting. Equally an assumption that the mid-point of forearm was the centre of gravity for measurements would have introduced error for a related reason. Hence, arbitrarily, a fixed point of 10cms proximal to the wrist crease, was selected as the point for application of force. Secondly, this study was not designed to (and was thus underpowered for) comparison of other issues of interest; such as difference in outcome of early versus late surgery, or single versus double nerve transfers. Thirdly it is accepted, that as with any clinical assessment tool, there are inter and intra-observer variations. These have been well documented (Tuttle 1913, Feiss 1912).



This deficiency of the study is acknowledged, but it is noted that these data are similar to the only other previously published series of continuously assessed outcomes (Carlsen et al. 2011, Martins 2013).

There is importance given by the research group to a recognition that peak force generation is a simplistic assessment of motor re-innervation outcome. There is, thus, a future challenge to identify methods to assess factors that our patients find confound their recovery, fatigability, tremor, lack of proprioception, co-contraction to identify but a few. The challenges implicit in the heterogeneity of human nerve injury and its outcomes are recognised. An exploration of the contribution of individual variability (age, nature of injury, distance from nerve transfer to target organ, time since injury, co-morbidities, gender etc.) will be informed through use of these measurements in comparative studies of the future.

To conclude, this study has characterised the left-shifted (from a normal population) population of re-innervated elbow flexion function: showing a Mean of 7.2 kgf (3 to 15.5;  $\pm 3.3$ ) at a mean of 56 months (28- 101 months) post operatively. The utility of a continuous quantitative measurement of outcome from muscle reinnervation has been demonstrated and will give patients an appreciation of their likely future recovery and holds the potential for playing a key role in future research for nerve injury recovery.

## 7.

**Validation of a consensus-based minimal clinically important difference (MCID) threshold in nerve transfer muscle re-animation, using an objective functional patient reported external anchor, an assessment of standard error of measurement, a Distributional Assessment and a Delphi group exercise.**

### **7.1 Overview and Summary**

#### **7.1.1 Background context:**

The minimal clinically important difference (MCID) is defined as ‘the smallest change in an outcome that a patient would perceive as meaningful. The Initiative on Methods, Measurement and Assessment in Clinical Trials (IMMPACT) group (2010) proposed defining the MCID as a 30% improvement in self-reported pain or function. However, this MCID threshold has not been validated against an objective physical measure.

Nerve transfer muscle re-animation is a treatment option for use when a nerve injury renders a muscle denervated and thus paralysed. The characteristics of the maximal elbow flexion force generated by individuals within a group with reinnervated biceps muscle have been demonstrated (Chapter six, Quick 2016) but there is no current method to manipulate the biologic response shown to improve on the results of this surgery. No drug efficacious to improve such outcomes. Identifying such a method to biologically improve nerve repair and nerve regeneration generally

is thought attractive. It is not known what the MCID would be for any such an intervention to improve outcome; what magnitude of effect would be noticed by patients. This is a significant gap in the knowledge necessary to progress such work.

#### **7.1.2 Summary Aim:**

To establish a valid range for MCID force of elbow flexion following muscle re-innervation nerve transfer surgery. Thus supporting a move towards an objective, measurable threshold that is patient-centred when aiming to improve motor outcomes.

#### **7.1.3 Summary Objectives:**

To use a range of accepted approaches to calculate MCID:

- Firstly, to utilise an ‘anchor method’: i.e. compare subjective, self-report measures of function with an objective measure of, the power generated from nerve transfer.
- Bring together an expert panel and explore the question through a Delphi exercise.
- Assess the spread of published results from nerve transfer operations to inform a ‘distribution method’ analysis of MCID.
- Analyse the likely standard error of measurement implicit in measuring elbow flexion force and consider this as a proxy for MCID via ‘SEM method’
- Finally, to assess a purely statistical method using a p value of 0.05 to calculate from published data a level of significant change.

#### **7.1.4 Summary of Study Design:**

A multiple point analysis of MCID was undertaken across a number of domains looking at what the additional force (KgF) generated by elbow flexion would have to be to reach a minimum clinically important (meaningful) improvement. This study draws on data from an assessment of force in Oberlin nerve transfer outcomes (Chapter 10).

#### **7.1.5 Summary of Patient Sample:**

The anchor population was a sample of 12 patients selected from the PNI Unit data base having developed elbow flexion from an Oberlin nerve transfer and being greater than 24 months from that surgery (as presented in Chapter 10). This cohort was examined by two observers (both independent therapists). The inter and intra observer assessments of these data has been used to inform the standard error or measurement calculation. The anchor based assessment relates to results of the MICD question (Chapter 6) taken from the same sample of patients. As detailed in Methods (7.1.17) Ethical approval was gained from the NHS ethical board after IRAS application.

**REC reference:** 16/LO/0623

**IRAS project ID:** 202847

#### **7.1.6 Summary of Outcome Measures:**

A survey of expectation of function was applied to all in the study to assess the actual or retrospective intention of post operative recovery. Questionnaires were completed by all post-operative patients to assess their impression of change following the surgery to re-innervate their elbow.

#### **7.1.7 Summary of Methods:**

MICD is a reported quantity with a great deal of uncertainty around its calculation. It is certainly a heterogeneous concept: At least 9 methods have been described as valid in calculating MCID

(Wright et al. 2012). In general, methodological approaches can be classified into two broad groups: anchor-based and distribution-based. Previous authors have outlined the strengths and weaknesses associated with these two methods; however, a single standardised methodology for calculating MCID has yet to be determined (Copay et al. 2007).

In this study a patient anchor assessment was gained from a retrospective sample of 13 patients who had recovered elbow flexion force following nerve transfer surgery. A Delphi assessment of 18 invited international experts in the field of nerve surgery provide their impression on MCID for motor recovery. Distribution-based approaches include a meta-analysis of a review of all published outcome series in the English language. Medline and PubMed and Google scholar were searched for publications including the search strings “outcome” AND “nerve transfer”, “biceps”, “elbow flexion” any publications not published in English were thus excluded 46 papers were identified. These papers were searched for outcomes quoted and a further 8 papers were identified from the bibliography searches. 56 papers were then searched for continuous outcomes measures and then further reduced to those that related to Oberlin nerve transfers. A calculation of the accepted errors of measurement and an assessment of Minimal detectable change are also included.

### 7.1.8 Summary of Results:

Method	Percentage improvement (taking the reference population as Quick 2016 7.2 Kgf (SD 3.3).	MCID elbow flexion force for Oberlin transfer
<b>IMPACT</b>	30%	2.16Kg
<b>Patient anchor</b>	90%	6.52Kg
<b>Delphi</b>	72%	5.16Kg
<b>SEM</b>	1SEM: 9-11%	650g-792g
<b>Distribution method</b>	21%	1.54KgF
<b>statistical p= 00.5</b>	70%	4.9 KgF

**Figure 7.1:**

Table demonstrating the multiple assessments of MCID calculated via differing methods and expressed as a force (KgF) and as a percentage change based on the published series Quick et al 2016. (Chapter 6)

### 7.1.9 Summary of Conclusions:

These data demonstrate a wide range of MCID values (figure 7.1) for MCID in the motor assessment of maximal volitional force assessment of re-innervated muscle (0.650Kg to 6.5 KgF). Such a spread of values is often reported in publications undertaking similar methodologies. The aim of MCID studies is to provide a unique threshold value, whereas, ironically, the different methods by necessity produce a range of MCID values. The range of an order of magnitude reflects this diversity of method.

## 7.2 Introduction

Surgery to address nerve injury has been accepted world wide as beneficial in selected cases to improve upon natural history. The proof of concept of the various methods deployed, (neurolysis, nerve repair, nerve grafting and nerve transfer) has been reached. The next stage necessitates a focus on the indications and to identify other methods to improve outcome. Advancing the state of the art is difficult due to indistinct classification systems (related to the huge variation in the injuries seen and the difficulties implicit in predicting outcome), outcome measures and standardising surgical treatments.

Nerve injury can affect some or all of the modalities of nerve function- movement, sensation, sweating, proprioception, pain etc. There are a number of validated measures used to assess these factors. Many of these measures are subjectively assessed and can vary widely due to external factors- (stress, physiology, temperature, analgesia etc.) The assessment of motor outcome has undergone an evolution in clinical assessment recently and is now regularly measured as a continuously assessed variable of maximal effort force. Peak force generate-able by maximal effort is standardisable and for certain muscle groups (elbow flexors) and easily and reproducibly assessable. Our previous published data (Chapter six, Quick et al. 2016) have shown a mean outcome of 7.2Kg of force (KgF) at a mean of 56 months (28- 101 months) with a SD of 3.3 KgF. This model has been chosen for study as the nerve transfer can be considered a 'standardised nerve injury'. The outcome from the nerve transfer is solely due to the repair and recovery is purely motor. The outcome is obvious to the patient and thus can be considered and discussed as an isolated outcome. We intend to use this model to assess the likely MCID of any intervention to improve upon the current level of force recovery following re-innervation. This improvement could be a systemic drug, a surgical technique improvement, a novel rehabilitation technique or local drug delivery at the point of nerve repair or transfer. For each of these an MCID in each facet of recovery (pain, sensation, sweating, proprioception) would be necessary

to detect any meaningful change - we only consider the return of motor function as assessed by the traditional peak force in this study.

### **7.3 Background**

Jaeschke (1989) first defined minimal clinically important difference (MCID) as being “*the smallest difference in score in the domain of interest which patients perceive as beneficial and which would mandate, in the absence of troublesome side effects and excessive cost, a change in the patient’s management*”. Variations and applications of this concept have varied (Beaton et al. 2002; Chung et al. 2017) but the concept of a threshold level of change in a given outcome which when crossed is seen by patients or clinicians as demonstrating an appreciable difference (Gatchel et al. 2013). The Initiative on Methods, Measurement, and Pain Assessment in Clinical Trials (IMMPACT) (Haythornthwaite 2010) group recommended that the MCID be defined as a 30% change in self-reported pain or function (Dworkin et al. 2005; Haythornthwaite 2010). However, this was a consensus decision based on a review of studies that used different methodologies. Subsequently, several other recommendations have been made, using both anchor-based and distribution-based MCID approaches (Gatchel & Mayer 2010; Copay et al. 2007; Chung et al. 2017). In order to apply these methods to investigate the parameters in the assessment of muscle re-innervation the following study was undertaken:

### **7.4 Study Design**

In the taxonomy of MCID it is difficult to develop a single method that offers validation across all aspects of assessment. MCID is often taken as an absolute value but we would support a more



nuanced view of the metric. We thus designed four parallel methods to assess the same outcome measure. (the outcome measure in question was an objective assessment of a continuous metric; elbow flexion force (KgF) in reinnervated elbow flexors).

A questionnaire has been used to capture subjects' views on what level of extra force would represent a MCID to them. Following this; a phenomenological assessment of patient lived experience of nerve transfer recovery of elbow flexion (detailed in chapter eight) was undertaken and free text anchor statements to assess patient cohort expectation are also provided.

Previously published data has been used of the outcome of nerve reinnervation results to analyse the MCID on a population basis (Quick 2016). Data taken from the previously presented Delphi group (chapter 5) where discussion on outcome measurement was held at two international meetings, following a presentation of the subject area and agreement made between the group. Finally, and most pragmatically; the standard error of measurement (SEm) was calculated (through a recognised method; Jacobson 1992, Rai 2015). This represents the minimal effect that could realistically be measured with the methods in use currently.

#### **7.4.1 Anchor based approach**

An anchor statement or questionnaire is a method to record a meaningful external 'anchor' which relates to the patients' experience. It is a self valid statement either a direct statement of outcome ( "I would want a two minute improvement in my walking distance," or "be able to perform that task 10 minutes quicker") or indirect such as a global impression of change. This can be used to delineate indirectly the MCID by cross-referencing the specific outcome point where there is a perceived population positive global impression of change. Thus we questioned a cohort of patients who had all had recovered the ability to lift weight following nerve transfer surgery. "What increase in force do you think that you would need to gain in order to notice the difference".

Participant	Gender	Age	Affected side	Dominance D-dominant ND-nonDom	Injury	Op date	HHD (Kgf)	
							Affected	Non Affected
1 GP	M	47	L	ND	Avulsion C5/6	27/08/14	14.03	19.18
2 LJ	M	27	L	ND	AvulsionC5 RuptureC6	02/10/15	16.27	29.62
3 SM	M	27	L	ND	UT neuroma	23/01/15	8.92	10.01
4 CW	F	69	L	ND	UT neuroma	17/09/10	6.33	15.63
5 MH	M	52	L	ND	UT neuroma	30/09/11	6.83	9.9
6 PA	M	44	L	ND	AvulsionC5 neuromaC6	23/05/14	9.57	25.61
7 SB	M	51	R	D	Avulsion C5/6	15/06/09	12.3	28.97
8 SP	F	47	R	D	Tumour upper trunk	06/07/98	3.12	19.76
9 TH	M	36	R	D	Avulsion C5/6	27/08/10	5.36	19.02
10 TB	M	53	R	D	Muscular cutaneous nerve humeral #	23/08/96	10.38	28.71
11 MM	M	43	L	D	Avulsion C5/6/7 +/-8	17/10/14	4.65	9.9
12 AW	M	50	L	ND	Avulsion C5/6/7	09/09/09	7.2	30.45

**Figure 7.2:**

Table of Patient demographics. The study cohort was n=12 subjects

(M10 F 2) mean age 45.5 (27-69) years.

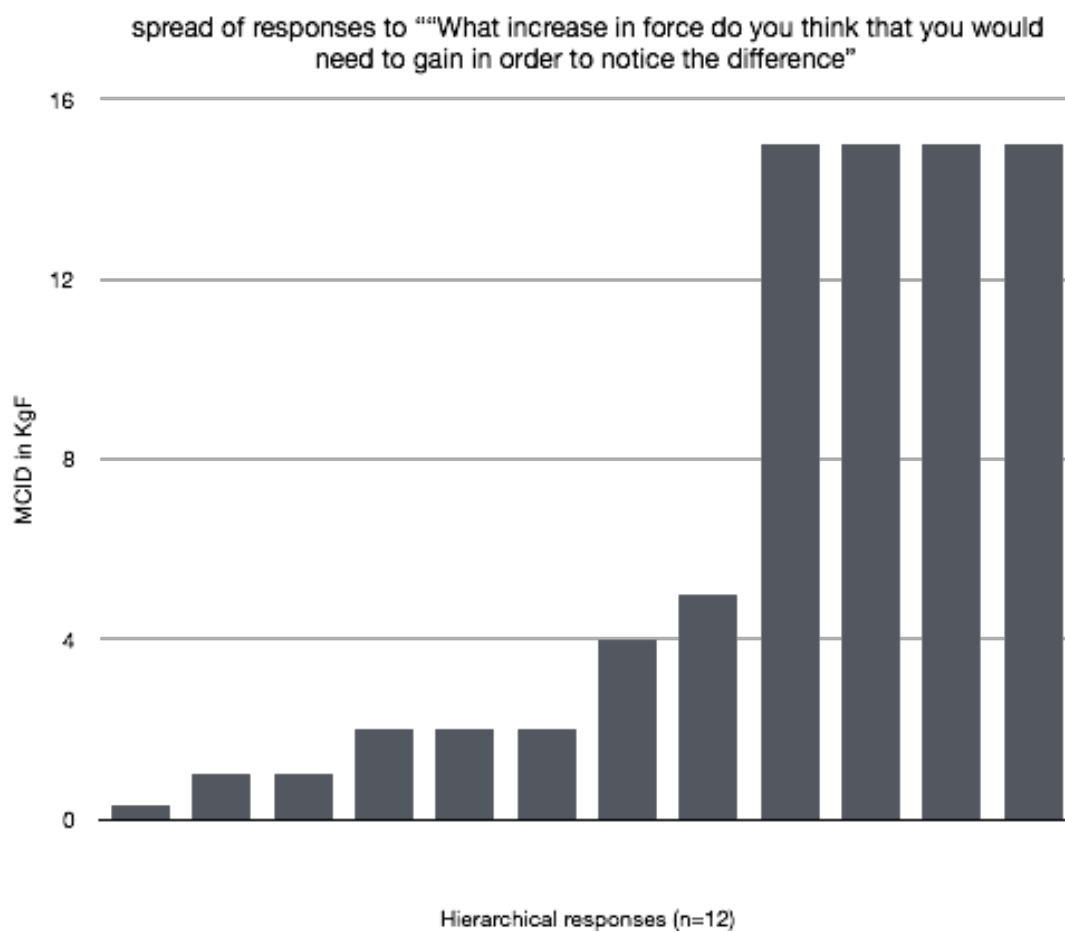
## **OUTCOMES MEASURES:**

This cohort of self-reported MCID was gathered using the anchor question:

*“What increase in force do you think that you would need to gain in order to notice the difference?”*

This was assessed with a possible range of answers:

- 50gs (approx. the weight of a chocolate bar)
- 100gs (approx. the weight of a tube of toothpaste)
- 300ga (approx. the weight of a small tin of beans)
- 500gs (approx. the weight of a 1/2litre bottle of water)
- 1Kg (approx. the weight of a litre bottle of water)
- 2Kg (approx. the weight of 4 pints of milk)
- 3Kg (approx. the weight of a 3 litre tin of paint)
- 5Kg (approx. the weight of a vacuum cleaner)
- 10Kg (approx. the weight of a lawnmower)
- 15Kg (approx. the weight of 12 bottles of wine)
- greater than 15Kg
- ADD “OTHER”



**Figure 7.3:**

Representation of spread of responses to a question of MCID.

Mean 6.53 KgF SD (6.419) N=12

MODE 15 KgF

RESULTS:

Descriptive Statistics	N	Minimum	Maximum	Mean	Std. Deviation
MCID	12	.30Kg	15.00Kg	6.52Kg	6.418

**Figure 7.4:**

Results of anchored patient assessment of MCID

There is a very large spread of numbers here and as shown by the histogram even the mode responses was split between two responses of 15 Kgs and 2kgs. To investigate this further we re-directed our focus to the current situation not a hypothetical improvement- We undertook comparison between the response to the question “what difference has this operation made to you” and the force recorded for 12 patients who attended for assessment of their force.

<b>The force of elbow flexion (KgF) following elbow flexion nerve transfer operation</b>	<b>What difference has this operation made to you</b>  <b>Likert response 0- none 5- a huge difference.</b>
<b>16.270</b>	5
<b>9.57</b>	5
<b>8.92</b>	5
<b>7.730</b>	5
<b>6.33</b>	5
<b>4.650</b>	5
<b>12.3</b>	4
<b>10.38</b>	4
<b>7.20</b>	4
<b>6.83</b>	4
<b>5.36</b>	4
<b>3.12</b>	0

**Figure 7.5:**

Results of subjective assessment of impression of impact (difference to patient) as measured by a Likert scale of returned force of elbow flexion (in KgF).

Further assessing the means of the groups who assessed 4/5 and 5/5 impression of change we find 5/5 (n=6 Mean 8.91KgF, SD 4.0) and 4/5 group (n=5 Mean 8.41KgF SD 2.8). A two tailed comparison of these two populations shows no significant difference between them.

Anchor-based methods have been criticised for the effect of recall bias on long-term responsiveness (Norman 1997, Stratford 1997) and it has been shown that retrospective report of change is reflective of the patient's current health status.

We further illustrate the disparity between groups in this analysis with selected significant phrases taken from a phenomenological analysis of a group discussion (n=5) on the patient experience of muscle re-innervation (Chapter 9)

*"just to move it was a reasonable outcome"*

*"any function is better than none so the force is kind of just the starting point "*

## **7.4.2 Delphi**

### **7.4.2.1 Method:**

Subjects: The author attended two international nerve injury meetings (Sunderland meeting Frankfurt September 2016 and the Scandinavian- UK Brachial Plexus meeting Stockholm May 2017) where this project was presented via a 3 minute presentation and a 7 minute question and answer session. An invite was extended to the assembled audience during this presentation to complete an online poll- 18 responders provided 12 answers to MCID.

To the request for an estimation of MCID there were three incomplete answers - 2 said they did not understand the question, one misunderstood the question (the response was; that to improve function they would do a Stendler flexoplasty- an operation to move the origin of the

flexor muscles of the forearm to effect an increase in elbow flexion vector to the pull of these muscles) and one answered that a MCID would be 50% of the patient's current function.

<b>DELPHI MCID- given a population with a mean force of 7Kg and a SD of 3.5 what is the minimal <i>additional</i> force that would be necessary for a patient to notice a clinically relevant improvement?</b> <b>n=12</b>																
<b>KGf</b>	0.5	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
<b>N</b>	1	1	4	2	0	1	0	1	0	0	1	0	0	1	0	0

**Figure 7.6:**

Table of Delphi responses of MCID for returned elbow flexion

	N	Minimum	Maximum	Mean	Std. Deviation
MCID Delphi	12	.50Kg	13.00Kg	5.16Kg	3.921

**Figure 7.7:**

Distribution of data from Figure 7.5

This result from a Delphi assessment of many international expert Brachial plexus surgeons- all of whom regularly perform nerve transfers for elbow flexion and clinically assess their own results. There is a much tighter distribution than we presented in the patient MCID. This represents then a common understanding of the area.

#### 7.4.2.2 Conclusion:

The Delphi group provide a mean of 5.16Kg which is very similar to the Patient group 6.52 KgF. This is at odds with Goldsmith's heuristic approach (Goldsmith et al. 1993) where it was argued that clinical experts would want to see more change in an individual's score before they confidently consider an important change to have occurred than in a group of patients' scores. There is considerable agreement between the two groups (subjective and objective assessment here).

However this simplifies the very different distribution of these data. In comparing the distribution of responses from the patients and the experts there is a narrower spread of MCIDs identified by the experts (Patient SD- 6.42. Delphi SD- 3.92).

#### 7.4.2.3 Discussion of Delphi Data:

This difference between the spread of results may reflect the fact that the Delphi group utilise force outcome assessment regularly (and have considered this concept prior to the study and have an innate preconception of what an MCID is in their own practice). It may also reflect weaknesses in the question design and/or method. These concepts have not been explored in the literature previously and so it is difficult to place these data in the context of others.

In that the subjective and objective means are similar and that motor assessment of peak power is often used as an objective assessment; it is suggested that this MCID is valid for these observers.

### 7.4.3 MCID (signal) versus the SEM measurement error (noise)

An assessment of an important change can only be useful if it is greater than the measurement error (Standard error of measurement SEM) is the error implicit in the system. The system can be considered as having two major compartments- the assessment and the assessed quantity. The



assessed quality first of all. We do not know the variation of the force from one moment to the next, is there day to day and moment to moment variation? Then does the assessment vary from time to time with a stable metric- this is the Intra-class correlation.

The intra-class correlation ( ICC) and Standard Error of measurement (SEm) are related, (Stratford & Goldsmith 1997) but they convey different information about the reliability of a measure. The standard error of measurement (SEm) estimates how repeated measures of a person on the same instrument tend to be distributed around his or her “true” score. The true score is always an unknown because no measure can be constructed that provides a perfect reflection of the true score (Stratford & Goldsmith 1997). In trying to assess the MCID we must acknowledge that if it is smaller than the SEm then it will be drowned out in this variation. The signal will not be detectable due to the noise. Thus it is argued that the SEm can be used as a minimum level for the MCID.

<b>INTER RATER AS- SESSMENT</b>	<b>Observer A mean (SD)</b>	<b>Observer B mean (SD)</b>	<b>Pearson Correlation</b>
Over 3 assessments	7.72 (3.70)	7.65 (3.50)	0.941** (.000)

**Figure 7.8:**

Inter-rater assessment of the mean of 3 assessments by two observers' (A and B) assessment of elbow flexion force following Oberlin using HHD.

\*\* significant value  $p < 0.05$

INTRA-RATER ASSESSMENT	Observer A1 Mean (SD)	Observer A2 Mean (SD)	Observer A3 Mean (SD)	Kappa correlation R=
Oberlin	7.47 (3.33)	7.61 (3.56)	7.87 (3.69)	A1-A2: 0.967** (0.000)  A1-A3: 0.958** (0.000)  A2-A3: 0.971** (0.000)

**Figure 7.9:**

Intra-rater assessment; Mean and SDs of 3 assessments (A1, A2, A3) by a single observer (A) Correlation of comparison between A1-2 A103 and A2-3 is demonstrated with Kappa R

\*\*significant value  $p < 0.05$

First to assess the SEM we must take the information from inter and intra rater observer variation of elbow flexion strength. When assessing the variation of repetitive assessments with inter-observer ( $R=0.941$  Rho) and intra-observer ( $R=0.958$ ) assessments of peak force there is little noise here.

#### 7.4.3.1 Methods for SEM method

Using the data from a study (presented in Chapter 10) on assessing force in Oberlin re-innervated elbow flexion. The Standard error of measurement (SEM) in turn, can be calculated from an analysis of a variance table (intra-class correlation or ICC) of repeated measures in stable patients, may be estimated by the following formula: SD times the square root of  $[2 \times (1 - R)]$  where R is the test-retest reliability coefficient (Jacobson 1992, Rai 2015). It should be noted that the original Jacobson formula did not include the factor of square root of 2 ( $= 1.41$ ) (Rai

2015). The R value for HHD assessment of peak force Oberlin transfer outcome is tabulated in Figure 7.9 [data from chapter 10 study].

#### 7.4.3.2 Calculation

Taking the SEM as calculated in relation to the Inter-class correlation

$$SEM = SD * (\sqrt{1 - ICC})$$

There is thus the following spread:

using the data from 2 observers assessing peak force of an affected limb post Oberlin transfer (figure 7.8) (data again from from Chapter 10) three times there is an ICC of 0.941.

$$SEM = SD * (\sqrt{1 - ICC})$$

$$SEM = 3.634 * (\sqrt{1 - 0.941})$$

$$\underline{SEM = 0.896} \text{ with the population mean being 7.685KgF (Quick et al. 2016)}$$

then **SEm% = 11%**

Using assessment by one observer assessing three peak contractions of a normal limb

$$SEM = SD * (\sqrt{1 - ICC})$$

$$SEM = 6.833 * (\sqrt{1 - 0.958})$$

$$\underline{SEM = 1.411} \text{ Kg with the population mean at 20KG}$$

then the **SEm% = 18%.**

#### 7.4.4 SEm in the literature

The literature provides SEm for hand held dynamometers as follows; Brogårdh et al 2015) noted in testing 28 patients with polio weakness of the upper limb using a Biodex System 3 PRO dynamometer (Biodex Medical Systems, Inc, Shirley, NY) the SEM% ranged from 12-16% in measuring isometric elbow flexion. Ekstrand (Ekstrand et al. 2015) using the same equipment in 2015 measured 45 patients post stroke and found SEm% 5.6-7.6% for elbow isometric flexion contraction. Most recently Liu in 2016 (Liu et al. 2016) in a study looking at improving the reliability of hand held dynamometers (using the HBO HHD Yueqing Haibao Instrument Co. Ltd., Zhejiang Province, China) noted a SEm% in isometric elbow flexion at 90 degrees of 9.8%.

Thus the theoretical calculated SEm is in the same range as that seen experimentally from this data.

#### 7.5 Distribution based approach

Distribution-based approaches to determining MCID scores are based on the statistical characteristics of published sample populations (and in turn on statistically significant changes in relation to the probability that the change has occurred by chance). One advantage of distribution based methods is the ability to account for change beyond some level of random variation. Conversely, a weakness of distribution-based methods is that there are few agreed upon benchmarks for establishing clinically significant improvement (MCID)- a circular argument for our purposes.

It is also important to recognise that distribution based methods do not address the question of the individual patient's perspective of MICD which is distinctly different from statistical significance across a population. Thus this method will produce an MCID which is applicable only in certain situations – studying population change for example.

#### 7.5.1 Method

In order to demonstrate the spread of published outcomes using a continuous measure a literature search An electronic search of three databases was undertaken (performed on October 18, 2017,) including Medline (1946-present), EMBASE (1974-present), and the Cochrane Central Register of Controlled Trials. The search strategy used the following MeSH terms: “brachial plexus”, “nerve transfer”, and “wounds and injuries”. Studies were initially screened for inclusion based upon titles and abstracts. If eligible, the full-text article was obtained and a final decision on inclusion was made. The bibliographies of included studies were also checked for additional citations. Inclusion criteria were studies evaluating intra- or extra-plexal nerve transfers to the musculocutaneous nerve or its distal branches to biceps and/or brachialis to restore elbow flexion in patients with traumatic brachial plexus palsy. Minimum follow-up had to be twelve months and surgery had to be performed within one year of injury. The primary outcome of interest was a continuous measure of elbow flexion strength, such as kilogram force (Kgf). If this was not reported, we recorded the absence of such data, but included the study if it measured our secondary outcomes of interest, including the MRC grade and elbow range of motion (ROM). Outcome data from eligible studies were extracted from the latest follow-up in all studies. Exclusion criteria included obstetrical brachial plexus birth palsies, paediatric patients, nerve transfers requiring an intervening nerve graft, cadaveric or non-human studies, isolated case reports, literature reviews, technique descriptions, expert opinions, and non-English articles. Studies were

also excluded if individual data for elbow flexion neurotization could not be extracted from the article.

After performing the above searches 46 papers were identified. These papers were searched for outcomes quoted and a further 8 papers were identified from the bibliographies within these publications. All 46 papers reported MRC grade outcomes. The table below shows the studies that quoted a continuous measure of force. In order to arrive at a weighted summated average of the results published in the highlighted papers (highlighted in grey in figure 7.11) the following calculation was followed based on research methodology advisory publications (Bravata and Olin 2001, Wan et al 2014).

Thus the following weighting of means was applied:

$$\text{Mean of total group reported} = (n_1 \cdot X_1 + n_2 \cdot X_2) / (n_1 + n_2)$$

Having made these assumptions, the following equation was used:

$n_1$  = No. of observations in 'paper 1'

$n_2$  = No. of observations in 'paper 1'

$X_1$  = mean of results in 'paper 1'.

$X_2$  = mean of results in 'paper 2'.

The following equation was to assess combined group variance:

$$\text{Variance of total group} = n_1 \cdot (S_1^2 + d_1^2) + n_2 \cdot (S_2^2 + d_2^2) / (n_1 + n_2)$$

$n_1$  = No. of observations in 'paper 1'

$n_2$  = No. of observations in 'paper 1'

$X_1$  = mean of 'paper 1'.

$X_2$  = mean of 'paper 2'.

$S_1^2$  = variance of 'paper 1'.

$S_2^2$  = variance of 'paper 2'.

$d_1$  =  $X_1$  - mean of total group

$d_2$  =  $X_2$  - mean of total group

The resultant weighted population mean and SD have been used to calculate a figure for MCID in a number of ways by Wright et al (2012). Wright in reviewing the literature describes a distribution based approach where the MCID is defined as follows.

$$MCID = X \times SD_{\text{baseline}} [\sqrt{(1-r)}]$$

Where X is set 1 for small effect, 1.96 for moderate or 2.77 for large effect. The calculation performed below utilises the figure of 2.77 (but also quotes the range of outcomes from 1-2.77). Wright (2012) also describes an approach where  $0.05 \times SD$  is used quoting arguments that an effect size of 5% is often considered a moderate effect. This approach is also calculated below.

## 7.5.2 Results

Paper	number of patients	Donor	Force recorded
Minami 1987	17	ICN	-
Kawai 1988	24	ICN	-
Nagano 1989	146	ICN	-
Nagano 1992	64	ICN	-
Chuang 1993	66	ICN	2.5kgF
Thomeer 1993	9	ICN	-
Malessy 1993	7	ICN	-
Oberlin 1994	4	Ulnar	-
Krakauer 1994	8	ICN	-
Ruch 1995	17	ICN	-
Songcharoen 1995	21	ICN	-
Ogino 1995	10	ICN	-
Leechavengvong 1998	32	Ulnar	2.7±1.8kgF
Brandt 1993	4	MP	-
Malessy 1998	25	ICN	-
Waikakul 1999	75	ICN	-
Okinaga 1999	5 (vasc)	ICN	-
	6 (contr)	ICN	-
El-Gammal 2002	20	ICN	-
Novak 2002	6	TDN	-
Sungpet 2003	36	Ulnar	1.8kgF
Xu 2002	15	Phrenic	-
Sungpet 2003b	5	Median	2.5kgF
Chalidapong 2004	19	ICN	-
Bertelli 2004	12	Ulnar	-
Bertelli 2004	10	Ulnar	-
Teboul 2004	32	Ulnar	2.6±2.5kgF
Mackinnon 2005	6	Ulnar/Med	-
Liverneaux 2006	10	Ulnar/Med	3.7±2KgF
Nath 2006	40	Median	-
Leechavengvongs 2006	15	Ulnar	2.6±2KgF
Goubier 2007	5	Ulnar/Med	6KgF
Stockinger 2008	1	Med pec	-
Venkatramani 2008	15	Ulnar	-
Bhandari 2008	23	Ulnar	-
Zyaei 2010	10	Ulnar	-
Coulet 2010	17	ICN	3.1±1.7KgF
	23	Ulnar	4.5±2.5KgF
Bertelli 2010	7	Ulnar	5.2±1.4KgF
Kakinoki 2010	8	Ulnar	-
	8	ICN	-



<b>Bhandari 2011</b>	26	Ulnar/Med	5.7±1.3KgF
	21	Ulnar/Med	5.8±1.5KgF
<b>Ray 2011</b>	29	Ulnar/Med	-
<b>Carlsen 2011</b>	23	Ulnar	8.94±5.92Nm
	32	Ulnar/Med	12.54±11.76Nm
<b>Estrella 2011</b>	9	Ulnar/Med	2.7±1.6 KgF
<b>Suzuki 2011</b>	8	Ulnar	-
<b>Dolan 2011</b>	12	Ulnar	-
	9	Ulnar/Med	-
<b>Naito 2012</b>	4	Ulnar	-
<b>Socolovsky 2012</b>	18	Ulnar	4.4±2.5KgF
<b>Martins 2013</b>	20	Ulnar	4.14±3.27KgF
	20	Ulnar/Med	5.6±2.41KgF
<b>Soldado 2014</b>	5	TDN	-
<b>Cho 2013</b>	8	Ulnar	-
	15	Median	-
<b>Schreiber 2014</b>	21 (normal EMG)	Ulnar	-
	6 (affected EMG)	Ulnar	-
<b>Xiao 2014</b>	30	ICN	-
<b>Socolovsky 2014</b>	40	Ulnar	5.8KgF
<b>Cho 2015</b>	19	ICN	-
<b>Yi-Jung Tsai 2015a</b>	16	ulnar nerve	4.3±2.7KgF
<b>Yi-Jung Tsai 2015b</b>	C5-C6 (9)	ulnar nerve	-
	C5-C7 (9)	ulnar nerve	-
<b>Quick 2016</b>	26	Ulnar	7.2±3.3KgF
<b>Frueh 2017</b>	6	ulnar nerve	-

**Figure 7.9:**

results of a literature review of papers reporting results for re-innervation of elbow flexion. Those highlighted in gray are assessment of Oberlin transfers which quoted a continuous measure of elbow flexion force. An electronic search of three databases was performed on October 18, 2017, including Medline (1946-present), EMBASE (1974-present), and the Cochrane Central Register of Controlled Trials. The search strategy used the following MeSH terms: “brachial plexus”, “nerve transfer”, and “wounds and injuries”. Inclusion criteria were studies evaluating intra- or extra-plexal nerve transfers to the musculocutaneous nerve or its distal branches to biceps and/or brachialis to restore elbow flexion in patients with traumatic brachial plexus palsy. Exclusion criteria included obstetrical brachial plexus birth palsies, pediatric patients, nerve transfers requiring an intervening nerve graft, cadaveric or non-human studies, isolated case reports, literature reviews, technique descriptions, expert opinions, and non-English articles. Studies were also excluded if individual data for elbow flexion neurotization could not be extracted from the article.

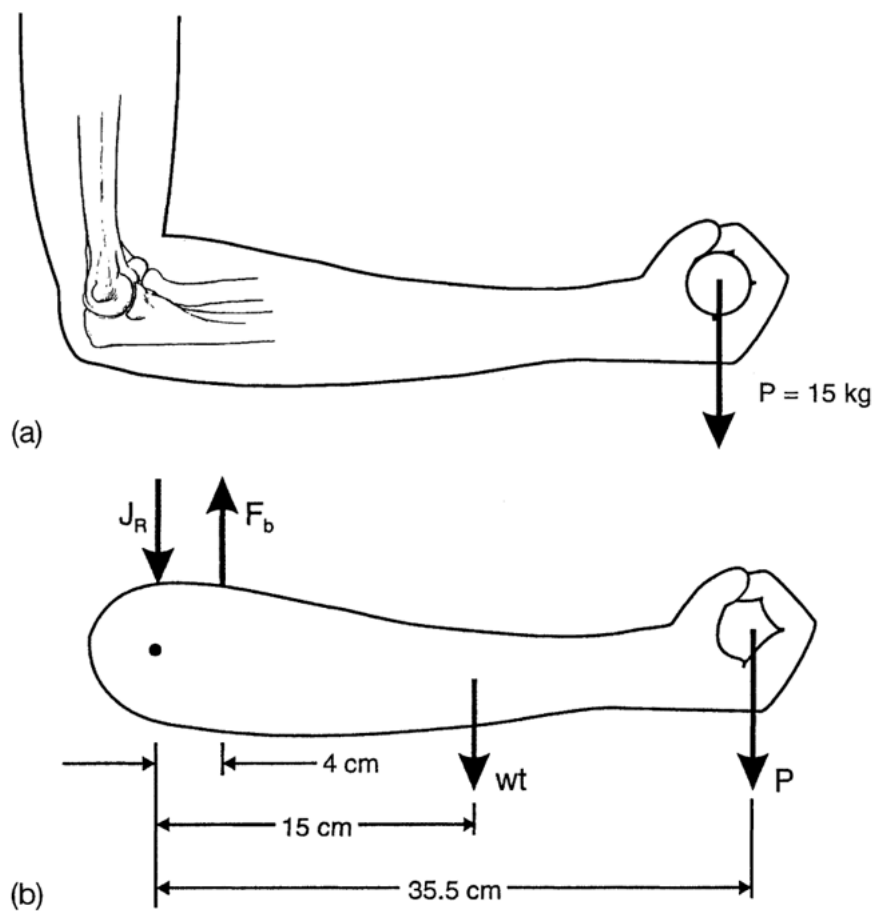


Figure 2.4. (a) The arm bent at 90° at the elbow, with the wrist and fingers held rigid and a weight of 15 kg held on the palm. (b) The free-body diagram of the forearm holding the weight.

**Figure 7.10:**

Free body diagram of force vectors around the elbow; from (Lucas et al. 2011)

The following papers were selected as they reported continuous force outcomes (figure 7.8).

(Chuang et al. 1993, Leechavengvongs et al. 1998, Sungpet et al. 2003, Tebul 2004, Liverneaux et al. 2006, Leechavengvongs et al. 2006, Coulet et al. 2010, Bertelli & Ghizoni 2010, Bhandari 2011, Carlsen 2011, Estrella 2011, Scolovsky 2012, 2014, Martiins 2013, Tsai 2015)

The papers reporting ICN transfers were further excluded to arrive at a meta-analysis on the outcomes for Oberlin (or double) Oberlin transfers (figure 7.10)

One paper (Carlsen et al. 2011) reported force in Nm; this was converted to Kg Meters (1Nm=0.10187KgMeters) then as per the biomechanical analysis in (Lucas et al. 2011) [Figure 7.10]. Then divided by 4, then multiplied by 35.5, to approximate the force likely to be measured at the radial styloid (assuming all elbow flexion function is via biceps). The subsequently derived data (8.09KgF and 11.27KgF) were both noted to be significant outliers. In that small changes in the multiplication value in the calculation is likely to produce a significantly different values for the mean these synthesised results were excluded from further analysis (figure 7.10).

<b>Chuang 1993</b>	66	ICN	2.5kg		
<b>Leechavengvong 1998</b>	32	Ulnar	2.7±1.8kg		
<b>Sungpet 2003</b>	36	Ulnar	1.8kg		
	5	Median	2.5kg		
<b>Teboul 2004</b>	32	Ulnar	2.6±2.5kg		
<b>Liverneaux 2006</b>	10	Ulnar/Med	3.7±2kg		
<b>Leechavengvongs 2006</b>	15	Ulnar	2.6±2kg		
<b>Goubier 2007</b>	5	Ulnar/Med	6kg		
<b>Coulet 2010</b>	17	ICN	3.1±1.7kg		
	23	Ulnar	4.5±2.5kg		
<b>Bertelli 2010</b>	7	Ulnar	5.2±1.4kg		
<b>Bhandari 2011</b>	26	Ulnar/Med	5.7±1.3kg		
	21	Ulnar/Med	5.8±1.5kg		
<b>Carlsen 2011</b>	23	Ulnar	8.94±5.92Nm	0.912 KgM	8.09 KgF
	32	Ulnar/Med	12.54±11.76Nm	1.27KgM	11.27 KgF
<b>Estrella 2011</b>	9	Ulnar/Med	2.7±1.6 kg		
<b>Socolovsky 2012</b>	18	Ulnar	4.4±2.5kg		
<b>Martins 2013</b>	20	Ulnar	4.14±3.27kg		
	20	Ulnar/Med	5.6±2.41kg		
<b>Socolovsky 2014</b>	40	Ulnar	5.8kg		
<b>Yi-Jung Tsai 2015a</b>	16	ulnar nerve	4.3±2.7kg		
<b>Quick 2016</b>	26	Ulnar	7.2±3.3kg		

**Figure 7.11:**

Tabulation of those identified as reporting continuous measures of force for elbow flexion. Papers included in the analysis in the text are highlighted in grey. Those excluded (in white): Chuang 1993 & Coulet 2010 excluded from the analysis of Oberlin as they were ICN transfers. Carlsen 2011 also excluded as the reported values were in Nm (shown in the table is an attempt at conversion towards KgF as discussed in the text.)

In order to arrive at a weighted summated average of the results published in the highlighted papers (highlighted in grey in figure 7.11) the following calculation was followed based on research methodology advisory publications as supported by Bravata and Olkin (2001) and Wan et al (2014).

Thus the following weighting of means was applied-

$$\text{Mean of total group reported} = (n1 \cdot X1 + n2 \cdot X2) / (n1 + n2)$$

Having made these assumptions the following equation was used:

$n1$  = No. of observations in 'paper 1'

$n2$  = No. of observations in 'paper 2'

$X1$  = mean of results in 'paper 1'.

$X2$  = mean of results in 'paper 2'.

$$(32 \cdot 2.7) + (36 \cdot 1.8) + (5 \cdot 2.5) + (32 \cdot 2.6) + (10 \cdot 3.7) + (15 \cdot 2.6) + (5 \cdot 6) + (23 \cdot 4.5) + (7 \cdot 5.2) + (26 \cdot 5.7) + (21 \cdot 5.8) + (9 \cdot 2.7) + (18 \cdot 4.4) + (20 \cdot 4.14) + (20 \cdot 5.6) + (40 \cdot 5.8) + (16 \cdot 4.3) + (26 \cdot 7.2) =$$

$$\text{Mean} = 86.4 + 64.8 + 12.5 + 83.2 + 37 + 39 + 30 + 103.5 + 36.4 + 148.2 + 121.8 + 24.3 + 79.2 + 82.8 + 112 + 232 + 68.8 + 187.2 = 1549.1 / 361$$

**Mean outcome from reported papers for elbow flexion following Oberlin outcome =**  
**4.29KgF**

To arrive at a weighted summated SD of these reports the following assumptions were made (Wan et al 2014)

- The quoted +/- ranges were 2SD ranges (thus they were halved and then squared to create the variance)
- Those without ranges quoted were assumed to have a SD of the average for the group.

Having made these assumptions a similar process was undertaken to calculate the weighted spread of the results.

For this, the following equation was used :

$$\text{Variance of total group} = n_1 \cdot (S_1^2 + d_1^2) + n_2 \cdot (S_2^2 + d_2^2) / (n_1 + n_2)$$

$n_1$  = No. of observations in 'paper 1'

$n_2$  = No. of observations in 'paper 1'

$X_1$  = mean of 'paper 1'.

$X_2$  = mean of 'paper 2'.

$S_1^2$  = variance of 'paper 1'.

$S_2^2$  = variance of 'paper 2'.

$d_1$  =  $X_1$  - mean of total group

$d_2$  =  $X_2$  - mean of total group

$$32 (0.81 + 4.29) + 36 (0.81 + 4.29) + 32 (1.56 + 4.29) + 10 (1 + 4.29) + 15 (1 + 4.29) + 23 (1.56 + 4.29) + 7 (0.49 + 4.29) + 26 (0.4225 + 4.29) + 21 (0.5625 + 4.29) + 9 (1.8225 + 4.29) + 18 (1.5625 + 4.29) + 20 (2.67 + 4.29) + 20 (1.452 + 4.29) + 16 (1.8225 + 4.29) + 26 (2.7225 + 4.29) / 311$$

$$163.2 + 183.6 + 187.2 + 52.9 + 79.35 + 134.55 + 33.46 + 122.525 + 101.9025 + 55.0125 + 105.345 + 139.2 + 114.84 + 97.8 + 182.325 / 311 = 1747.21/311 = 5.27$$

Thus SD = Square root of 5.27 = 2.2956

**SD = 2.3**

**Thus the average outcome from reported papers for elbow flexion following Oberlin outcome is 4.29KgF +/- 4.59Kg (range of 0 - 8.88KgF)**

**In order to calculate MCID from this calculated weighted population data the following calculations have been applied:**

$$MCID = X \times SD_{baseline} [\sqrt{(1-r)}]$$

Where X is set at 1 for a small effect and 1.96 for moderate and 2.77 for a large effect and the test-retest intra-class correlation coefficient (ICC) of stable patients is used for r. The larger effect size has been

Thus:

$$MCID = 2.77 \times 2.3 [\text{Sq Root}(1-0.941)]$$

$$MCID = 2.77 \times 2.3(0.243)$$

**MCID as related to the spread of data in the published series is:**

**MCID = 1.54KgF**

*(If the effect size had been deemed small and the X set at 1 the MCID would = 0.56KgF)*

**Statistical method (MCID = 0.5SD)**

**It has been argued in published work (Wright 2012) that a figure for MCID could be 5% of the SD of the population Standard deviation.**

MCID=0.5 SD of the  $\Delta$ score

the change here being the development of force of elbow flexion ie = mean force

MCID= 0.5 (2.3) 4.29KgF

**MCID as calculated as p= 0.5 is:**

**MCID = 4.9KgF**

## **7.6 Conclusions**

The stated aim in this study was to establish a valid range for MCID in force of elbow flexion following muscle re-innervation nerve transfer surgery. Thus supporting a move towards an objective, measurable threshold that is patient-centred when aiming to improve motor outcomes. It has been shown (in Table 7.1) that a range of MCIDs may be applicable, from 0.65KgF-6.5KgF. This is a variation of an order of magnitude. This relates from a 10% change (as calculated from SEM to a 90% difference as assessed by patients. Such a spread of values is often reported in publications undertaking similar methodologies.

The figures quoted relate to population figures; they are suitable for application in trial design (allowing a power analysis to be properly calculated) or to support QUALY information. They do *not* relate to the impact of the operation of re-innervation of muscle following nerve injury in individuals. An individual MCID will be unrelated to the methods used in this study (other than the anchor question – but this again is a summation of a large range of individual responses).

There is no literature specifically relating to this area previously published and as such its relationship with other data cannot be directly explored. These data are applicable to any study assessing any improvement in outcome from an Oberlin nerve transfer as they inform the discussion as to what the minimal change any study should be powered to demonstrate.

Methods such as these demonstrated in this chapter should be applied with a recognition of the need to identify not just the success of realising a reliable change but combine this with a criterion for clinical significance. “Better” is defined by MCID; the realm of how much ‘better’ should be calculated using one of these methods- an anchor-based approach, a meaningful percent change criterion, or statistical criteria for clinical significance. In this way change is identified correctly as reliable *and* clinically significant.

## **7.7 Discussion**

In using SEm% to calculate a MCID Wyrwich (2004) noted that to attaining a 1.96 or 2.77 SEm threshold for classifying important improvements in abnormal individuals (Jacobson et al. 1999), while others consistently advocate that 1 SEm is the crucial minimum threshold for demonstrating individual change (Schaie & Willis 1986). If we look at our calculated SEm from our study then we note that a range 2.77-3.9Kg as a MCID (calculated as 1.96-2.77 x SEm) provides on our study population mean range of 27-53%.



It is not uncommon that such a variation in MCID is found even in one study Terwee et al. (2010) found five different MCID scores, ranging from 24.2 to 18.9 points (with 95% of the values lying between 214.9 and 13.8) for the WOMAC physical function subscale when using five different MCID methods much in the same way as this paper. One possible explanation is that different MCID methods result in different MCID scores due to the multiple reported conceptual and methodological differences

Whilst the SEm method has been supported by many experienced authors in this area it is significantly challenged in this area of technological advancement as with improvement in technology it is likely that internal standard errors of measurement decrease and thus the SEm will deviate from any historic values.

The aim of MCID studies is to provide a unique threshold value, whereas, ironically, the different methods by necessity produce a range of MCID values. Anchor-based methods will produce different MCID depending on the criterion scale and the arbitrary selection or grouping of scale levels. Conceptually, a minimal difference is a difference between two adjacent levels on a scale, such as “unchanged” and “slightly better.” MCID would then depend on the number of levels on a scale: the larger the number of levels, the smaller the difference between two adjacent levels, and the smaller the MCID. Ostelo et al. (2008) supported this premise when the authors reported a wide range of MCID scores on commonly used back pain outcome measures. In this study, the reported MCID score for the Oswestry disability index reportedly ranged from 2.0 to 8.6 points on a 100-point scale.

It is interesting to consider the potential uses that an MCID value would be put to: All of the methods used in this study produce a population MCID other than the anchor question. From this data the MCID may properly be deployed to inform the calculation of a power assessment in study design or assess efficacy of an intervention for assessment of health economics (QUALY

calculation etc). However it speaks little to the experience of any particular individual. For the individual the range of MCIDs is reflected in the raw data of the subjective study (from 0.3Kg – 15Kg). Thus it is important to recognise the method utilised to arrive at any MCID prior to applying to any specific use.

The definition of MCID requires some further thought when the intervention is surgical. We accept Jaeschke's definition (1989) for MCID but feel the addition of the concept of minimal clinically acceptable difference (MCAD) is also important. The ratio MCID: MCAD would reflect the *perceived* inherent risk of the intervention under discussion. If it were a physical therapy intervention then MCID and MCAD would near a 1:1 relationship. If it were to be a life essential intervention (organ transplant for example) then the ratio would drop hugely with the difference in symptoms thought to be noticeable would be tempered by what the patient was willing to risk to gain any improvement. In this field of study the MCID for nerve transfer surgery and augmentation of that outcome with drug therapy may be similar but MCAD for each would be different. (MCAD= perceived risk vs perceived benefit of MCID.)

To progress this project it is intended to prospectively collect data as patients reneurotise their biceps and thus follow the subjective peak force from not being able to lift the arm to being able to lift weight and link this with subjective scores of satisfaction and assessment of impact percentage scoring. We intend to compare this peak power change (as patients improve over time) with the receiver operating characteristic curve (ROC) to determine the change in score of the patient reported outcome (PRO) with the smallest difference between sensitivity and specificity to identify MCID. The area under the curve (AUC) represents the ability of the chosen MCID value to correctly discriminate improved and non-improved patients, with AUC values approaching 1.0 representing excellent discrimination. This methodology will allow a more dynamic assessment of the range for individual's rate than the population scores we have assessed here

between what threshold is clinically important for a cohort. It could be that the peak force assessment is not a valid tool to assess outcome; that is not seen by patients as directly representing a clinical difference.

Further the implication of health economics to the landscape of outcome assessment is key to the political environment we all practice thus we offer a quantification of MCID to QALY value. The interplay of the involvement of these has never been addressed as far as can be seen from a literature review.

Whilst the information on MCID for maximal volitional contraction is likely to be helpful in designing future trials, the greatest benefit from this process to the author has been to realise the complexity of the patient experience in nerve injury recovery. The truth of assessing recovery from nerve injury is that recovery of full motor function can be useless to the patient if there is debilitating allodynia or parasthesia. Motor power assessment without an assessment of proprioception and fatigability and control can be meaningless. To this end we have set out to build a stream of research towards combining the objective assessments with a global subjective experience of recovery from nerve injury. We can then start to build a picture of which interventions benefit which aspects of nerve injury, what percentage improvement can be expected and at what risk to which population. It will also provide a view of the true benefit of our interventions against which we can grade improvements in the treatment available. i.e. if a new drug or procedure is used what level of improvement is gained. Furthermore, the minimum quantum of improvement that is noticed or valued by individual patients is not known.

## 8.

# Does recovery of peak force correlate with patients' perception of outcome?

Subjective assessment of successful re-innervation leading to return of elbow flexion.

### 8.1.1 Overview

Oberlin et al (1994) described a nerve transfer to reinnervate elbow flexion and thus improve arm function. It is performed with the aim of returning sufficient elbow flexion force to lift weight. Traditionally, surgical success is measured by the return of power and assessed by Maximal Peak Force (MPF) but is this outcome, in isolation, significant to patients?

This study has been designed to explore whether peak power is a parameter that is meaningful to the patient. Patient satisfaction with outcome is often complicated and can include aspects such as: what an individual anticipated to achieve and what has made a difference to their day to day function.

To the authors' knowledge there has been no published data on subjective assessment and in particular, the patient's opinion of their outcome following an Oberlin procedure.

### 8.1.2 Method

Study participants were recruited from the hospital database and comprised of 18 patients who were at least 24 months post double Oberlin transfer. The study received institutional ethical approval and informed consent was given by all participants.

A mixed methods approach was adopted whereby the cohort underwent a quantitative assessment (maximal peak force (KgF) and completed a subjective questionnaire regarding the patient's view of their individual recovery.

This study set out with the null hypothesis (H0) that patient satisfaction with outcome would be directly related to the level of recovery of elbow flexion force (as measured by peak power).

Ethical approval was gained from the NHS ethical board after IRAS application.

### **8.1.3 Results**

Despite Maximal Peak Force (MPF) being the most commonly assessed outcome following nerve transfer surgery is shown to not be a responsive or representative outcome measure to reflect the patient experience of muscle re-innervation. There was no significant correlation between the commonly used outcome measure of peak power and the patient's perception of the impact on their life (R 0.488 with a non-significant level of evidence  $p=0.108$ ).

Patients significantly under-estimate the outcome of surgery as assessed by a comparison of the subjective assessment and objective measurement of elbow flexion peak force. There is significant correlation between the patients' assessment of their current function and expectation attainment. Whereas, objectively measured force was strongly correlated with patients' assessment of difference ( $r=0.619$   $P=0.006$ ).

Patient satisfaction levels were universally high with 100% of respondents reporting that they would both recommend the operation to others and undergo the same procedure if they were back in the same situation. As all patients had regained power of elbow flexion as was the aim of the operation this is not surprising. Of the cohort 11/16 (61%) rated the impact as having had made a huge difference to them.

It is thus demonstrated that patients do notice the difference of having greater peak force but do not translate that into their assessment of impact.

#### **8.1.4 Conclusion**

Satisfaction with this nerve transfer operation to reinnervate elbow flexion shows no correlation with how much force (KgF) against gravity the biceps muscle can provide. When correlation was sought between a range of subjective assessment questions and force outcome there was some degree of face validity when using peak force as an outcome measure. However, this study begins to provide some evidence to support the necessity of a multimodal assessment to reflect a complicated picture of motor recovery. There is no related literature in the field of nerve injury on which to reflect.

## **8.2 Introduction**

Loss of active elbow flexion creates a considerable deficit in function. Activities such as hand to mouth for feeding and hand to midline to allow for independent dressing are commonly reported functional goals. Nerve injuries to the upper trunk, lateral cord and musculocutaneous nerve can all result in the loss of active biceps contraction.

## **8.3 Measurements of surgical outcome**

Traditionally, clinicians have used maximal peak force (measured by MRC grade) as a primary outcome measure. Hand Held Dynamometry (HHD) has been identified as a method to give a valid and continuous numerical value to force outcome assessment. A previous study within our institute examined the maximal force outcomes following Oberlin Transfer using HHD (Quick et

al. 2016). The benefits of ease of use and utility within a clinical environment were also highlighted. The results produced a continuous metric of KgF normally distributed around 7.2KgF for this patient group (Quick et al., 2016). Data was consistent with a previous study which reported strength to be around 1/3 that of the uninjured contralateral limb (Carlsen et al. 2011). HHD therefore seems to be a useful method to measure peak force outcome within this cohort.

Within the clinic environment it is common for many postoperative patients to report pain, fatigue and difficulty placing the arm to be limiting factors to their everyday life. Anecdotally the weight they can lift in a single maximal contraction is seldom raised as an issue. Nevertheless, in the literature it is peak force that is almost universally used to assess outcome of muscle rener-  
vation procedures.

The World Health Organisation (WHO) developed the International Classification of Functioning, Disability and Health (ICF) as a framework for measuring health and disability at both individual and population levels (WHO, 2001). In this framework both muscle function and the person's perceptions are considered alongside their ability to participate in everyday activities. This reflects the change in modern day healthcare where patient perceptions and satisfaction are considered with equal status to a clinician's "objective" outcome. Recent analysis of outcome following nerve injury has endorsed the use of patient-reported outcomes and functional assessments (Novak et al. 2009, Ahmed-Labib et al. 2007, Kitajima et al. 2006). A literature search on subjective and patient reported outcome measures (PROMs) of Oberlin transfer or nerve transfer produced no results. This represents a significant void in the literature.

Information regarding patient reported outcome in Oberlin transfer could provide a framework for clinicians to better tailor their assessment towards patient experience. Furthermore, the assessment of patient experience may thus provide information on how to improve patient satisfaction with their care.

## **8.4: Aims, objectives & Methodology**

### **8.4.1 Study question:**

- Is there a positive correlation between an individual's reported satisfaction with their outcome and the amount of elbow flexion strength that is regained following renervation surgery?

### **8.4.2 Aims:**

1. Identify a cohort of Oberlin transfer patients with documented MRC grade 4 recovery of elbow flexion at greater than 2 years post-operatively.
2. Design and administer a questionnaire to assess patient perception, expectation and satisfaction with surgical outcome.
3. Carry out a standardised peak force assessment using HHD for comparison with the subjective findings from the questionnaire.

### **8.4.3 Objectives:**

1. To use a mixed methods format to gain information on the impression patients had of their outcome.
2. To collect patients' assessment of their own peak power and whether they thought they had attained their original expectation of outcome.
3. To assess if patient satisfaction correlated with the degree of muscle strength of elbow flexion or attainment of preoperative expectation.
4. To assess a cohort of patients to assess whether difference within attainment of peak power outcome is reflected in satisfaction



## 8.5 Hypotheses

Null Hypothesis (H0): Patient assessment of satisfaction in their outcome is directly related to their recovery of force (as measured by Maximal Peak Force).

Primary Hypothesis (H1): Patient assessment of satisfaction in their outcome is not directly related to their recovery of force (as measured by Maximal Volitional Force).

## 8.6 Materials and Methods

Ethical approval was gained from the NHS ethical board after IRAS application.

**REC reference:** 16/LO/0623

**IRAS project ID:** 202847

The hospital database was examined to identify patients who were at a point greater than 24 months following Oberlin nerve transfer. These individuals were then further reviewed against the inclusion and exclusion criteria which included documented recovery of a minimum of MRC grade IV within their medical records (full criteria is outlined in Table 8.1). Sixty-two patients were identified as being eligible to participate in the study. All participants were contacted by post with a letter to invite them to complete an online questionnaire and to attend a clinical review. If no response was received after one month a second invitation letter was sent. A total of 18 patients were recruited in the study; of these 12 participants attended for a force outcome assessment.

Inclusion	Exclusion
Oberlin/double Oberlin transfer – treated with standard post-operative regimen  >24 months post surgery  Documented activity of elbow flexion of grade 4 MRC or above from clinical notes  Adult 18+	Oberlin transfer <24months post surgery  Oberlin transfer >24 months post surgery with MRC <3  Oberlin transfer >24 months post surgery proceeded to free functioning muscle transfer  Child (0 -18 years)

**Figure 8.1:**

Inclusion / Exclusion criteria.

The time period of 24 months post surgery was chosen by consensus agreement between the researchers as a suitable period for full motor recovery to have occurred. Clinically, after this time, there is very little evidence of further reinnervation. All patients underwent a standard regimen of post operative rehabilitation; an initial immobilisation period of 6 weeks followed by a milestone driven process of passive mobilisation, active movement and strengthening when signs of reinnervation returned.

A mixed methods approach was adopted whereby a subjective qualitative questionnaire focusing on satisfaction and participant's opinions relating to their motor recovery was compared to an objective quantitative maximal force outcome measured using a HHD (Biometrics Ltd, Cwmfelinfach Wales).

### **8.6.1 Stage 1. Subjective data collection**


The qualitative questionnaire was designed by the researchers (TQ, HB and KJ) utilising a mixed approach of discrete, framework supported and Likert questions to pose questions around the concepts of interest (impression of current function, expectation of function, minimal accepted

expectation of function, impression of change and impact of change). These were then developed into an online 'Google forms' survey (Google Inc. Mountain View, California, United States). The questionnaire commenced with an animated video of an isolated elbow flexion motion to focus the mind of the responder. Additional text was provided to direct respondents to solely consider elbow flexion as they answered the questions. In order to gather as much information as possible tick box, Likert scales and free text entry functions were utilised.

**Patient outcome assessment**

Please answer all of the questions with your gut feeling; don't over think your response.

This video shows the elbow joint: It is this movement (of bending the elbow) which we are now going to ask you about.



How much are you currently able to bend your elbow?

☐ I am unable to bend my elbow unless I use another part of my body to bend it

**Figure 8.2:**

Screen grab from Google Forms assessment tool questionnaire.

The questionnaire focused on various elements of recovery to explore different dimensions of patient experience. The themes included patient/participants' assessment of their current force of elbow flexion, a percentage assessment of their overall elbow function, their hopes preoperatively, their minimum expectation and their impression of change following the renervation and the impact this change has had. Finally, standard frequently used questions, such as those in

the Friends and Family test (NHS England 2014), guided questions towards the subjects' perception and finally satisfaction of their outcome (for example; would they recommend the surgery to others? and would they chose to have the surgery again?).

#### **8.6.2 Stage 2. Objective Quantitative data**

In order to anchor the answers to the questionnaire 12 of the 18 patients (67%) agreed to attend an assessment of their maximal peak force MPF. This assessment was carried out by 2 experienced therapists (HB and KJ). The assessment protocol utilises a HHD (Biometrics Ltd, Cwmfelinfach Wales) and is described in a previous publication (Quick et al. 2016). During this assessment; participants were asked to relate and disclose the maximal weight in kilograms that they believe that they can lift using their biceps muscle (i.e. elbow flexion). These were related to everyday objects (such as: 2kgs is approximately a four-pint bottle of milk and 5kgs approximately the weight of a vacuum cleaner). The validity of the test is shown by inter-observer  $R = 0.958$  and intra-observer reliability  $R = 0.941$  of the test is documented in figures 7.8 and 7.9.

	<b>Question:</b>	<b>Question focus:</b>	<b>Quantification</b>
<b>Q1</b>	How much are you currently able to bend your elbow?	Current function/ Subjective assessment	Discrete; statements describing MRC
<b>Q2</b>	Before surgery I would have realistically hoped to...	Pre operative Expectation/ Hope	Discrete; statements describing MRC
<b>Q2b</b>	..be able to lift the following with operated arm alone.		Discrete KgF with anchor statements
<b>Q3</b>	Before surgery I would have agreed to go ahead only if I could have realistically expected to...	Minimum Expectation	Discrete; statements describing MRC
<b>Q4</b>	A normal elbow is one which is pain-free, has full range of movement, normal strength and allows you to do what you feel your elbow should allow you to do this is scored at 100% (10/10). 0/10 is no function. How would you score your elbow?	SPONEA	Percentage assessed function with definition of range
<b>Q5</b>	How much do you think that your elbow function has improved since your surgery?	Impression of Change/ Improvement	Likert scale with each point defined 0-6
<b>Q6</b>	What difference has this operation made to you?	Impression of Impact/Difference	Likert scale with end points defined 0-6
<b>Q7</b>	Would you recommend this operation to somebody else (who has had the same injury as you) to improve their ability to bend their elbow?	Satisfaction	Binary Y/N
<b>Q8</b>	With your current knowledge, if we were to take you back in time to before the operation would you say yes to the offer of an operation to gain movement in your elbow?	Satisfaction	Binary Y/N

**Figure 8.3.**

Summary of focus of subjective assessment tool questions.

## **8.7 Results:**

18 patients (15 Male and 3 Female) consented to participate in stage one of the study (qualitative questionnaire). Of these, 12 (10 males and 2 females) proceeded to stage two (quantitative muscle force assessment). The mean age of the participants was 45 years (27- 69 years old). Right hand dominance (RHD) was reported in 16 participants with the remaining 2 being left handed (LHD). Injured dominant side 10, non-dominant 8 (dominant 5, non-dominant 7) The days since injury at time of assessment were an average of 2704.17 (range 642-7227). Full results and demographics are presented in Figure 8.4.

Participant	Gender	Age	Injured side	Injured side	Injury	Op date	Peak Force (Kgf)	SPONEA (/10)
1	M	47	L	ND	Avulsion C5/6	27/08/14	7.73	7
2	M	27	L	ND	Avulsion C5 Rupture C6	02/10/15	16.27	7
3	M	27	L	ND	UT neuroma	23/01/15	8.92	5
4	F	69	L	ND	UT neuroma	17/09/10	6.33	5
5	M	52	L	ND	UT neuroma	30/09/11	6.83	5
6	M	44	L	ND	C5 Avulsion C6 neuroma	23/05/14	9.57	1
7	M	51	R	D	Avulsion C5/6	15/06/09	12.3	4
8	F	47	R	D	Tumour upper trunk	06/07/98	3.12	1
9	M	36	R	D	Avulsion C5/6	27/08/10	5.36	4
10	M	53	R	D	MCN Rupture Humeral fracture	23/08/96	10.38	5
11	M	43	L	D	Avulsion C5/6/7 +/-8	17/10/14	4.65	3
12	M	50	L	ND	Avulsion C5/6/7	09/09/09	7.21	5
13	M	41	R	D	Avulsion C 5/6	01/09/14		6
14	M	51	L	ND	Avulsion C5/6/7	11/02/15		0
15	M	29	R	D	Avulsion C5/6	31/01/14		2

16	M	26	L	D	Avulsion C5/6 Rupture C7/8	05/03/08		5
17	F	45	R	D	MCN iatrogenic	20/11/15		6
18	M	59	R	D	MCN Rupture Humeral fracture	15/04/15		7

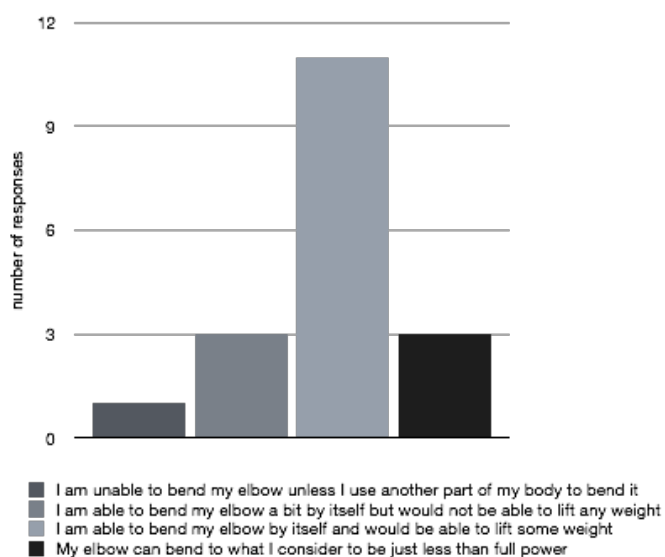
**Figure 8.4:**

Research Subjects demographics & information (first n=12 have force data) In the text the numbers quoted first (and highlighted in bold) are the group of n=12 who both completed the questionnaire and underwent an objective assessment of their peak force.

### **Stage 1. Subjective Outcomes.**

#### **8.7.1 Q1. How much are you currently able to bend your elbow.**

All subjects by selection criteria had recovered MRC grade 4.



**Figure 8.5**

.Bar chart representing answers to Q1. "How much are you currently able to bend your elbow?"



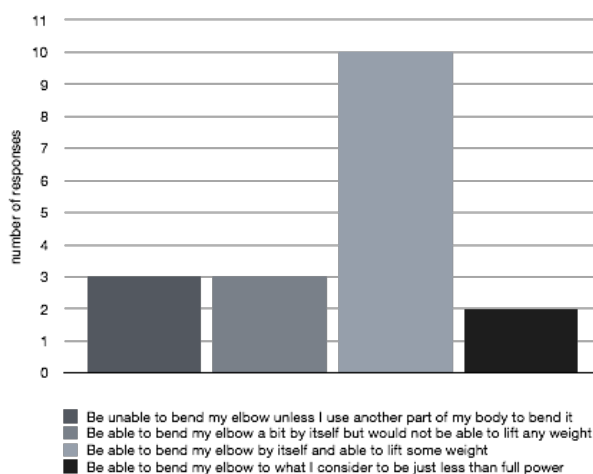
Current force assessment n=18	MRC Equivalent (/5)	No. (/18)
I am unable to bend my elbow unless I use another part of my body to bend it	1 or 2	1
I am able to bend my elbow a bit by itself but would not be able to lift any weight	3	3
I am able to bend my elbow by itself and would be able to lift some weight	4	11
My elbow can bend to what I consider to be just less than full power	5	3

**Figure 8.6:**

Tabulated results for Q1. How much are you currently able to bend your elbow?

**Commentary on Q1:** 14/18 (78%) identified that the restoration of innervation to the elbow flexors has allowed them to lift some weight. This corresponds with at least MRC grade IV classification. 4/18 (22%) report that the return of power is insufficient to lift a weight.

### 8.7.2 Q2a. Before surgery I would have realistically hoped to...



**Figure 8.7:**

Bar chart representation for results for Q2a. Before surgery I would have realistically hoped to ...

Before surgery I would have realistically hoped to...(Expectation)	MRC Equivalent (/5)	No.(/18)
Be unable to bend my elbow unless I use another part of my body to bend it	1 – 2	3
Be able to bend my elbow a bit by itself but would not be able to lift any weight	3	3
Be able to bend my elbow by itself and able to lift some weight	4	10
Be able to bend my elbow to what I consider to be just less than full power	5	2

**Figure 8.8:**

Tabulated representation for results for Q2. Before surgery I would have realistically hoped to ...

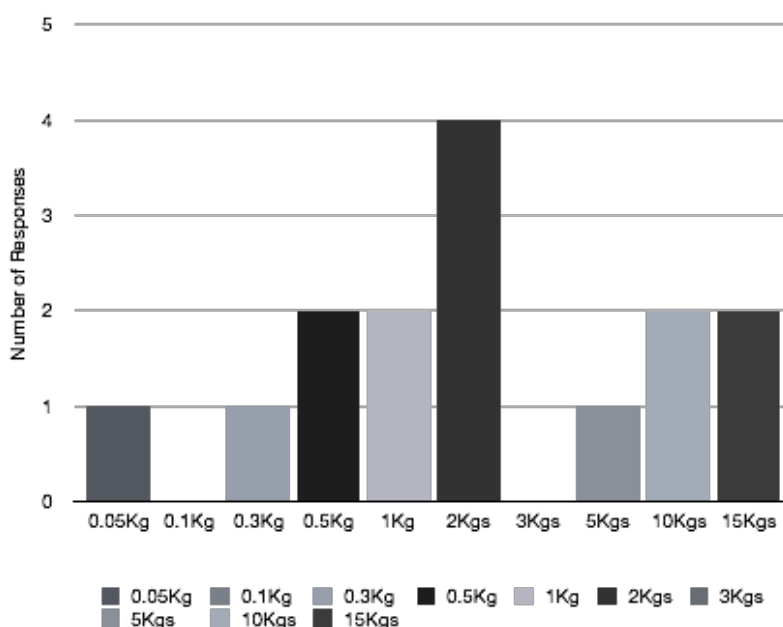
**Q2b. Before surgery I would have realistically hoped to lift the following with the operated arm alone.**

<b>Before surgery I would have realistically hoped to lift the following with the operated arm alone</b> (Expectation)	MRC Equivalent (/5)	No. (/18)
50gs (approx. the weight of a chocolate bar)	4	1
100gs (approx. the weight of a tube of tooth paste)	4	0
300gs (approx. the weight of a small tin of beans)	4	1
500gs (approx the weight of a small bottle of water)	4	2
1kg (approx the weight of a litre bottle of water)	4	2
2kgs (approx the weight of a 4 pint bottle of milk)	4	4

3kgs (approx the weight of 3 litre tin of paint)	4	0
5kgs (approx the weight of a vacuum cleaner)	4	1
10kgs (approx the weight of a lawn mower )	4/5?	2
15kgs (approx the weight of 12 bottles of wine )	5	2

**Figure 8.9:**

Tabulated representation for results for Qb2. Before surgery I would have realistically hoped to ... (n=1 “Depends on how much I have trained the muscles” n=1 did not answer n=1 “I can lift a heavy weight but not using biceps”



**Table 8.10:**

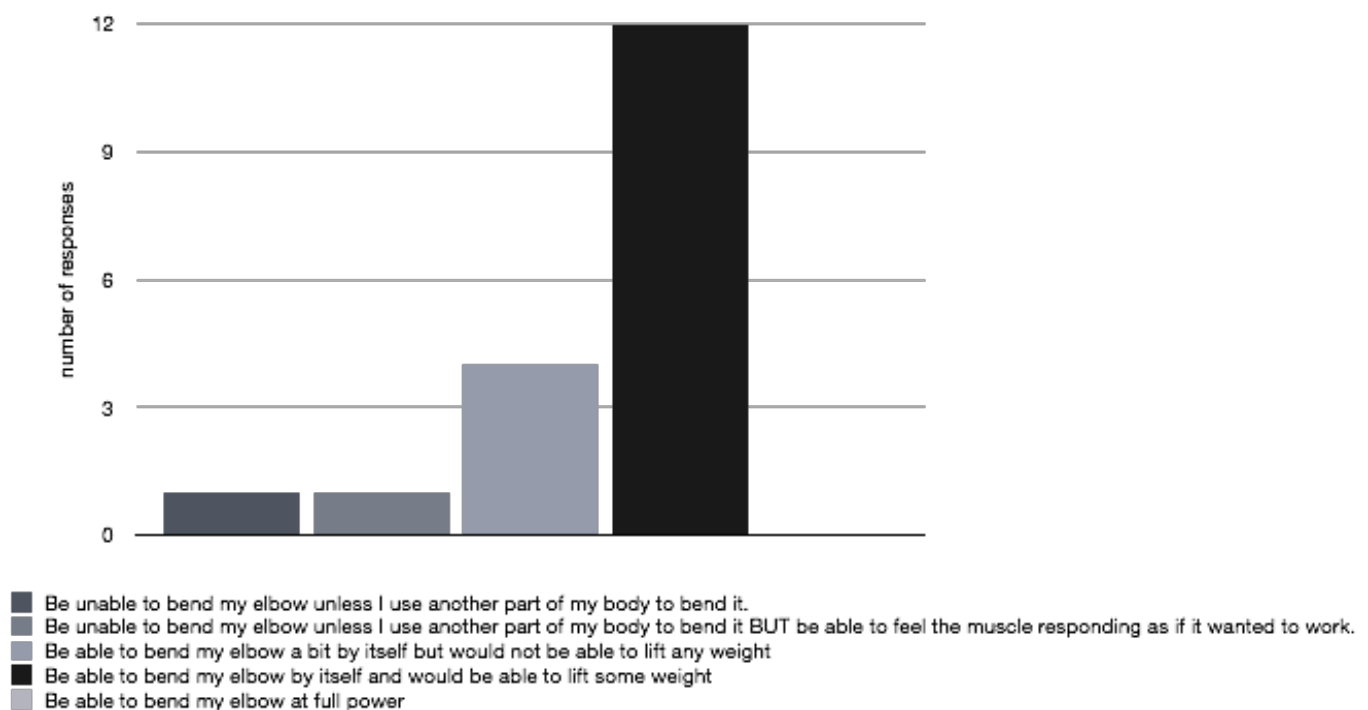
Bar chat representation for results for Q2b. Before surgery I would have realistically hoped to ...

### Commentary on Q2a and b:

The findings from Q2a MRC questions show that 3/18 (17%) patients hoped to achieve the equivalent of MRC grade V (normal or just less than normal – accepting 95-100% being near normal and classically classified as MRC 5/5). 11/18 (61%) expected MRC 4/5 power, 3/18 (17%) hoped for MRC 3/5 and finally, 1/12 (8%) expected MRC 2/5 or less.

In Q2b a level of internal dissonance is demonstrated as 15 patients stated they would have MRC 4+ power. (n=3 either did not answer or stated they didn't use biceps to lift a heavy weight or they stated "it depends on how much I have trained the muscle". This distribution tri-modal and has an overall mean resonance as 4 KgF the mode is 2kgF.

### 8.7.3 Q3. Before surgery I would have agreed to go ahead only if I could have realistically expected to...



**Figure 8.11:**

Bar Chart representation for results for Q3. Before surgery I would have agreed to go ahead only if I could have realistically expected to.

I would only have gone ahead with surgery if I could have realistically <b>expected</b> to... n=18	MRC Equiv- alent (/5)	No. (/18)
Be unable to bend my elbow unless I use another part of my body to bend it.	0	1
Be unable to bend my elbow unless I use another part of my body to bend it BUT be able to feel the muscle responding as if it wanted to work.	1 – 2	1
Be able to bend my elbow a bit by itself but would not be able to lift any weight	3	4
Be able to bend my elbow by itself and would be able to lift some weight	4	12
Be able to bend my elbow at full power	5	0

**Figure 8.12:**

Tabulated results for Q3. Before surgery I would have agreed to go ahead only if I could have  
realistically expected to...

### **Commentary on Q3:**

This question aimed to assess a minimal expectation level (what the patient *expected as a minimum*) in order to give consent to surgery. 12/18 (67%) *expected as a minimum* to achieve MRC grade IV recovery. This is well within the boundaries of any series of Oberlin outcome results. It represents a real and attainable expectation.

It is interesting that 2/18 (11%) would have been happy with no visible functional improvement and 6/18 (23%) would have been happy to proceed if they could have as a minimum expected no functional improvement.

**Review of Q1, Q2 & Q3:**

<b>MRC Grade</b>	<b>Cohort Actual* Outcome (Clinically as- sessed)</b>	<b>Cohort self As- sessed <i>Present Out- come</i></b>	<b>Cohort <i>Realistic</i> Expectation of Outcome</b>	<b>Cohort Mini- mum Expecta- tion of Out- come</b>
<b>0/5</b>	-	-	-	-
<b>1/5</b>	-	-	-	<b>1</b>
<b>2/5</b>	-	<b>1</b>	<b>3</b>	<b>1</b>
<b>3/5</b>	-	<b>3</b>	<b>3</b>	<b>4</b>
<b>4/5</b>	<b>18</b>	<b>11</b>	<b>10</b>	<b>12</b>
<b>5/5</b>	-	<b>3</b>	<b>2</b>	-

**Figure 8.13:**

Tabulated results for Q1, Q2& Q3. To demonstrate the number of the cohort in each category of MRC force (\* this cohort was purposefully selected to be MRC grade 4)

<b>MRC GRADE</b>				
<b>&gt;/ =4/5</b>				
<b>Population** actual</b>	<b>Cohort actual*</b>	<b>Cohort as- sessed</b>	<b>Cohort ex- pected</b>	<b>Cohort mini- mum</b>
<b>80%</b>	<b>100%</b>	<b>78%</b>	<b>67%</b>	<b>67%</b>

**Figure 8.14:**

Tabulated results to demonstrate the percentage of the cohort for each category with function (MRC>/=4) (\* this cohort was selected to be MRC grade 4) (\*\*expectation of an MRC 4+ outcome following Oberlin transfer in non selected standard population)

Table 8.13 demonstrates the shifting distribution of where the cohort currently believes themselves to be (despite a purposeful sample of MRC grade IV being selected for the study). The table shows where the cohort had hoped they would be (expectation of outcome) and the spread of expectations which they would have considered as a minimum to consent to surgery. Table 8.14 displays these same concepts as a percentage of the cohort at or above MRC 4 (a commonly quoted outcome in the literature).

In summary, when Qs 1,2 and 3 are reviewed in relation to one another the following can be asserted:

The (retrospectively assessed) expectation or hope of the procedure was for 78% greater than, or equal to MRC grade IV. This is in line with published rates of outcome from Oberlin procedure and thus represents a realistic expectation.

However only 14/18 (78%) stated that they thought they had attained MRC grade IV despite being purposely included in the study based on a documented clinical record of grade IV being achieved.

This suggests that the remaining 22% did not achieve their expected level of strength or force (a Negative Expectation Attainment). It may therefore be surmised that subjective impression of change is less than the objective observer may think.

Two thirds of participants expected as a minimum to attain their expectation: The minimum expectation assessment relates 12/18 hoping for function (elbow flexion  $\geq$  MRC IV) and expectation relates the same figure 12/18 hoping to gain at least some function to lift weight.

- Interestingly 2/12 patients' minimum expectation was no functional return whereas 3 stated they expected they would get no functional return. i.e. 2 subjects were happy to go ahead with surgery even if they got no function and one was happy to go ahead only

if they could as a minimum expect a flicker of activity but actually realistically expected to get no function.

However, 33% predicted they would not achieve their expectation of the benefit of the operation (a negative predicted personal experience: NPPE).

#### Objective Anchor comparison with Q2b

12 participants attended for stage 2 (objective force assessment) the force they generated in objective testing was compared with what they predicted the maximal weight that they could lift with their affected arm.

#### ***Actual current function: (Objective force assessment data)***

n=12:(7.73/16.27/8.92/6.33/6.83/9.57/12.30/3.12/5.36/10.38/4.65/7.2 KgF) mean 78.22  
(range3.12-16.27 ) SD 3.59

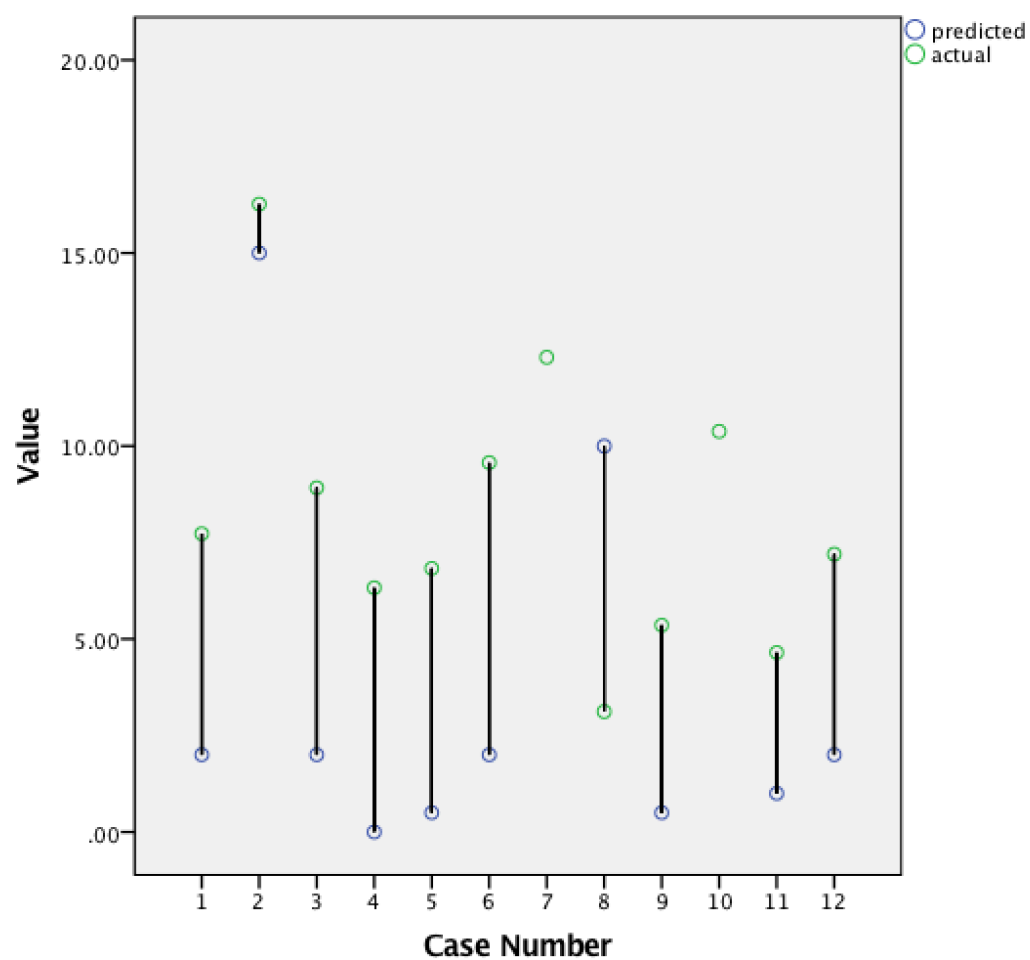
**Patient assessed current function (Subjective assessment anchor question)** “At 2 years post nerve transfer surgery I am able to lift”:

The same n=12: (2/15/2/0/0.5/2/depends/10/0.5/0/1/2) Kg mean 3.5 (range0-15 SD 4.94)

These are two differing groups with differing means:

A paired samples analysis n=10 (2 predicted values missing thus excluded) shows a difference of -4.1Kg between the mean (predicted being lower than actual) with a 95 CI between -7.1 and -1.1) t=3.044 and significance (2 tailed) of 0.014. That is to say; the average subjective assessment of our patients was to attain a lesser outcome than demonstrated they could lift, or we can say there was an average over-attainment or a positive expectation mismatch.



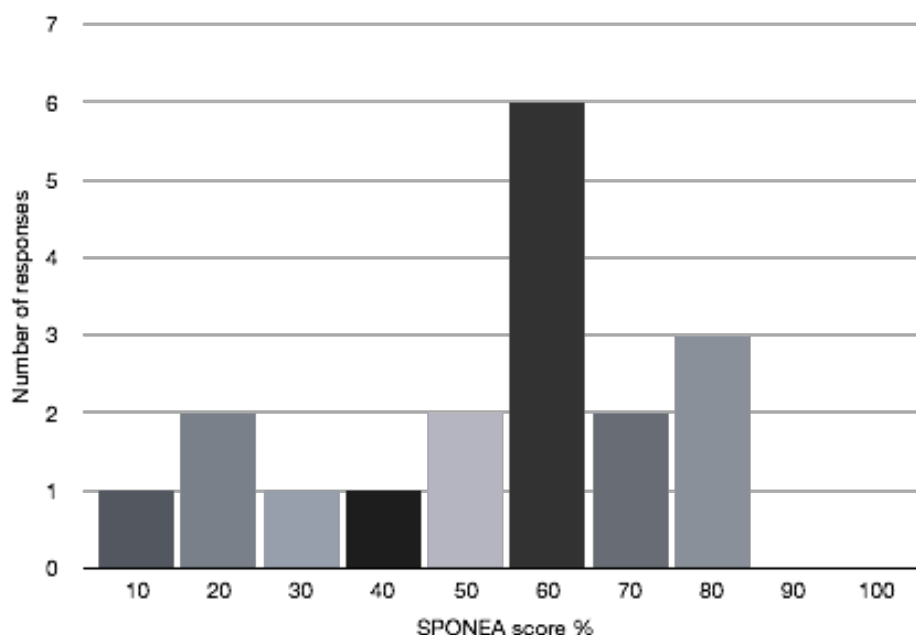


**Figure 8.15:**

a paired data analysis of Expectation mismatch- blue circles are the value the patients prediction (subjective assessment) and in Green the actual or (objectively) observed KgF of elbow flexion

**8.7.4 Q4. A normal elbow is one which is pain-free, has full range of movement, normal strength and allows you to do what you feel your elbow should allow you to do this is scored at 100% (10/10). 0/10 is no function. How would you score your elbow? [SPONEA]**

**N=18**



**Figure 8.16:**

Bar Chart results to demonstrate the SPONEA outcome.

SPONEA										
A normal elbow is one which is pain-free, has full range of movement, normal strength and allows you to do what you feel your elbow should allow you to do this is scored at 100%										
%	10	20	30	40	50	60	70	80	90	100
N	1	2	1	1	2	6	2	3	0	0

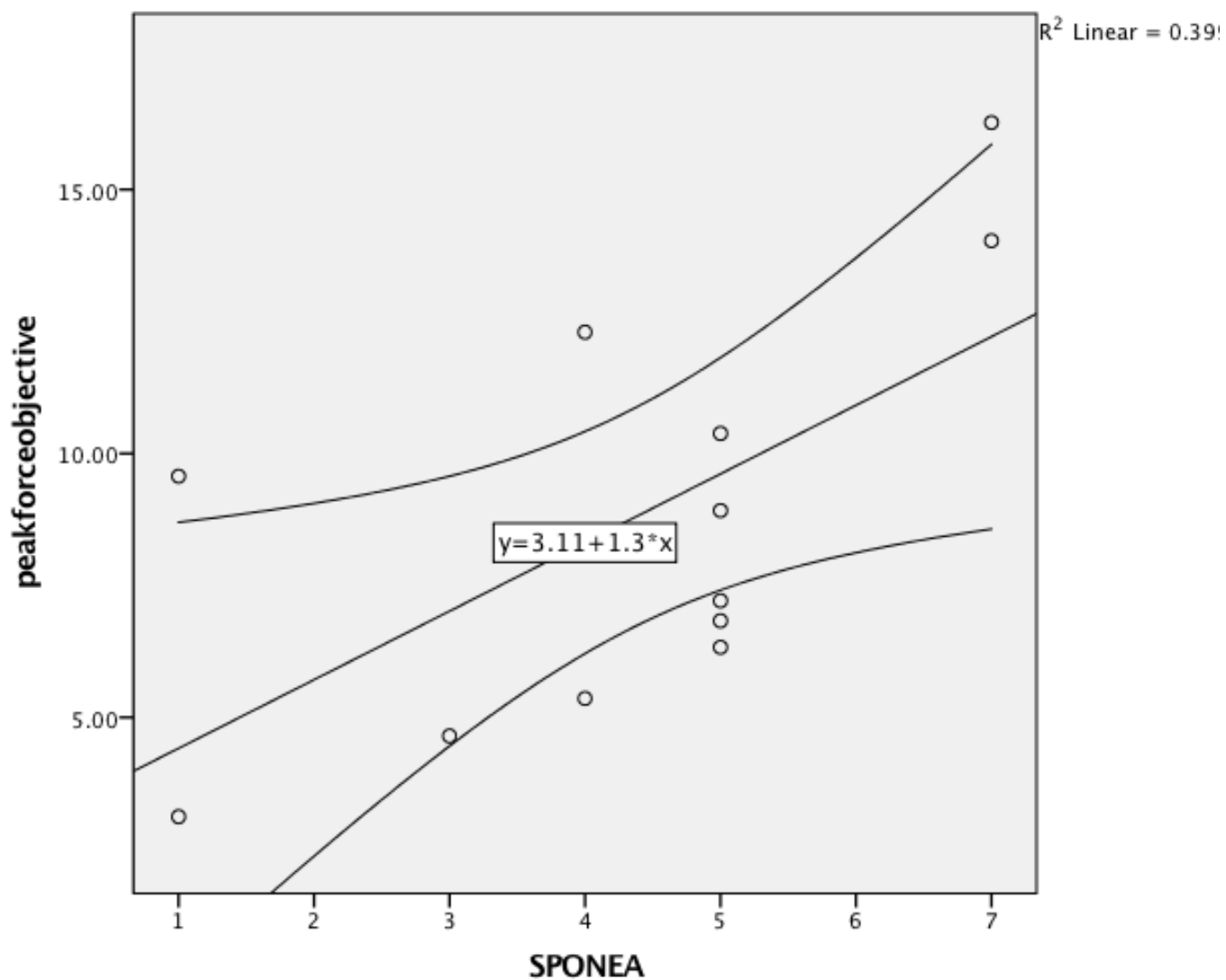
N=18 mode 5 mean 4.3 (range0-8) SD 2.14

**Figure 8.17:**

Tabulation of responses to the SPONEA question.

#### Commentary on Q4:

When the subjective SPONEA is compared with the MPF scores there is a definite relationship between the two as demonstrated by a Pearson's correlation of 0.604 with a two tailed significance of 0.008.

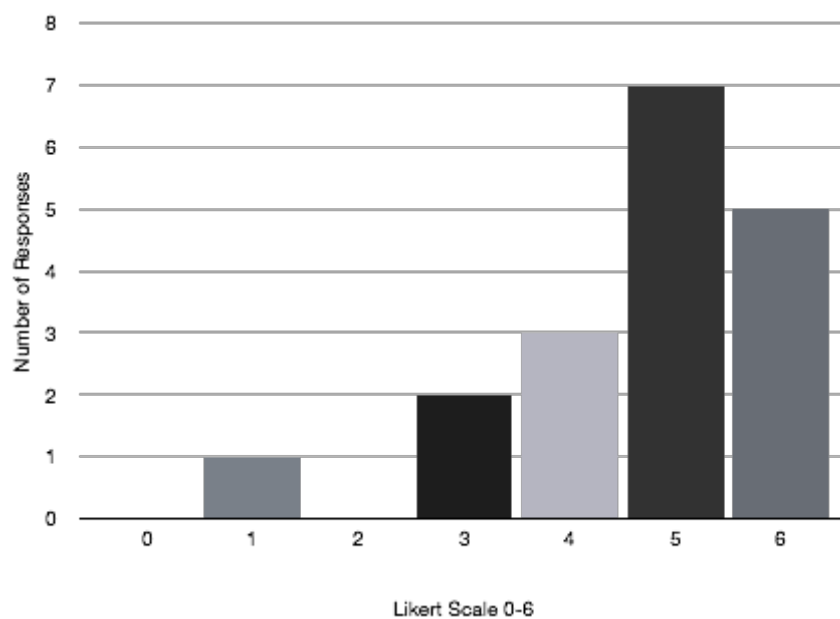


**Figure 8.18:**

Funnel Scatter plot of SPONEA against Objectively assessed peak force with a linear best fit surrounded by 95% CI.

**8.7.5 Q5. How much do you think that your elbow function has improved since your surgery?**

- 1. No change (or condition has got worse).*
- 2. Almost the same, hardly any change at all.*
- 3. A little better, but no noticeable improvement in my function.*
- 4. Somewhat better, but the change has made no noticeable improvement in my function.*
- 5. Moderately better with a slight but noticeable change in my function.*
- 6. Better with a definite improvement that has made a real and worthwhile difference in my function.*
- 7. A great deal better with a considerable improvement that has made all the difference in my function.*



**Figure 8.19:**

Bar chart results to demonstrate impression of change since surgery. Plot of overall satisfaction Likert Scale no better (1) – a great deal better (7)- mode = 5 mean= 4.78

**Q5. How much do you think that your elbow function has improved since your surgery?**

- 0- No change**
- 1- Almost the same hardly any change at all.**
- 2- A little better, but no noticeable improvement in my function.**
- 3- Somewhat better, but the change has made no noticeable improvement in my function.**
- 4- Moderately better with a slight but noticeable change in my function.**
- 5- Better with a definite improvement that has made a real and worthwhile difference in my function.**
- 6- A great deal better with a considerable improvement that has made all the difference in my function**

change	0	1	2	3	4	5	6
n	0	1	0	2	3	7	5

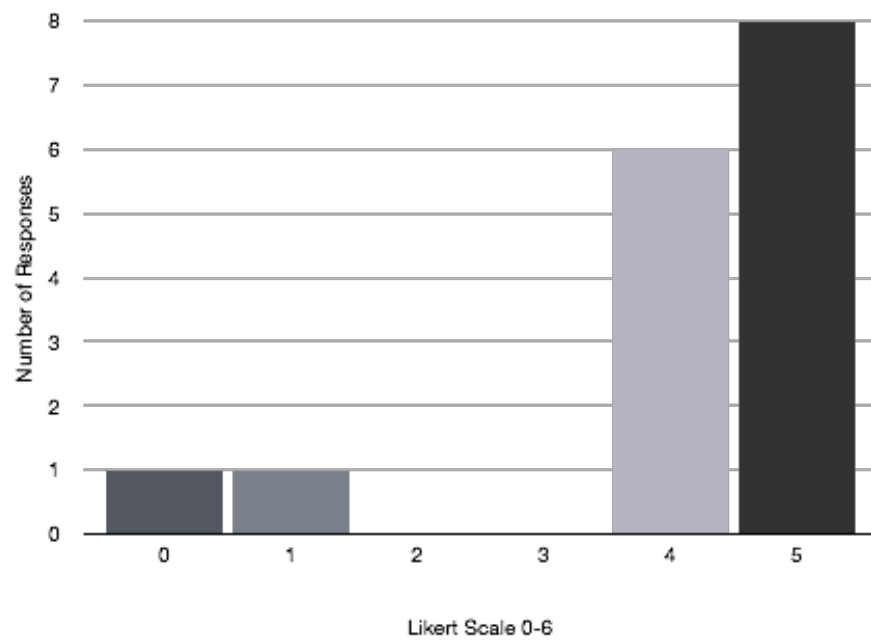
**Figure 8.20:**

Tabulated results to Q5.

**Commentary on Q5:**

The mode of 5 represents another facet of the patient experience – “moderately better with a slight but noticeable change” and with 12/18 rating the change as noticeable or better.

**8.7.6 Q6a.what difference has this made from 0 (no difference) - 5 (a huge difference)**



**Figure 8.21:**

Bar chart results to Q6. Demonstrating the subjective impact of the re-innervation

(0)- no difference to (5) a huge difference

<b>Q6 what difference has this made from 0 (no difference) - 5 (a huge difference)</b>  <b>0- No change</b>  <b>5- A huge difference</b>						
<b>Difference</b>	<b>0</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>
<b>N</b>	<b>1</b>	<b>1</b>	<b>0</b>	<b>0</b>	<b>6</b>	<b>10</b>

**Figure 8.22:**

Bar chart results to demonstrate distribution of difference made 5: huge difference to 0: no difference. N=18  
Mean 4.22/5, Mode 5/5 SD 1.309.

Characterisation of groups by assessment of impact

	<u>N</u>	<u>Mean</u>	<u>Std. Deviation</u>	<u>Std. Error Mean</u>
<u>force of those with impact 5/5</u>	8	9.9600	4.44762	1.81573
<u>force of those with less than 5/5</u>	8	7.4150	3.43892	1.40393

Comparison of groups by assessment of impact

	<u>t</u>	<u>n</u>	<u>Sig 2t</u>	<u>Mean Diff</u>	<u>95% CI</u>
<u>force of those with impact 5/5</u>	5.485	8	p=.003*	9.96000	5.2925-14.6275
<u>force of those with less than 5/5</u>	5.282	8	p=.003*	7.41500	3.8061-11.0239

**Figure 8.23:**

Comparison of groups by assessment of impact. Two groups were created those who deemed the impact 5/5 (a huge difference) and those who did not; the peak Force they developed were compared in KgF.

Free text entry following question on degree of impact of recovery.

*"Can move my arm where as before it was useless."*

*"Can still do my job as a heavy plant engineer"*

*"Because my arm was completely useless before the surgery yes I would like it to be better and continue to try to improve it!"*

*"I went from a totally non functional arm to Semi-functional."*

*"My arm was totally dead. The ability to move the elbow and hold or lift light items is a great comfort. It also offers some worthwhile useful functions when cooking, dressing or carrying things."*

*"I had no function in my arm and limited movement. No I have some and it is getting stronger"*

*"No difference at all really, but to be fair it was a long time ago and it was a long shot to get my elbow moving again!"*

*"Prior to my operation I had very limited use of my arm. I can not be sure that the operation has been the sole reason for progress, I do believe 'other' muscles compensate."*

*"Although not perfect, to one that doesn't know, it all looks and operates quite normal though my arm tires very quickly."*

*"Before the operation I had no movement at all in my left arm and now I have quite a bit of muscle contraction. So I think that it has definitely made a huge difference."*

*"Prior to my op, I had no biceps / triceps function - now both work to a reasonable / useful level"*



*“Living through the progress”*

*“Prior to operation the whole left arm from shoulder to hand did not have any function. along with tendon transfers & nerve surgery this operation has transformed my daily living.”*

*“As a PE teacher and a right arm injury the flex ion of my arm is essential to work.”*

*“Before was unable to move now I have full movement with not many restrictions in what I can do. I would recommend it to anyone”*

These qualitative data provides texture to the qualitative subjective experience where the impact is rated as a Mean 4.22/5, Mode 5/5 SD 1.309.

#### **Commentary on Q6a and b:**

There is significant population difference when the means of those individuals who stated the operation has made a 5/5 huge difference (n=6, 9.96 KgF) with those who graded it as less than this (n=6, 7.42 KgF). However, 16/18 of the respondents graded the impact as 4/5 or greater therefore this difference is less clinically relevant. The respondent who graded the impact as 0/5 scored an MPF of 3.12KgF. The overall satisfaction with the impact is 4.78/5 satisfaction. Over 50% (10/18) scored 5/5. The majority (11/12) reported a 4/5 or 5/5 difference.

#### **8.7.7 Q7. Would you recommend it to another with the same problem?**

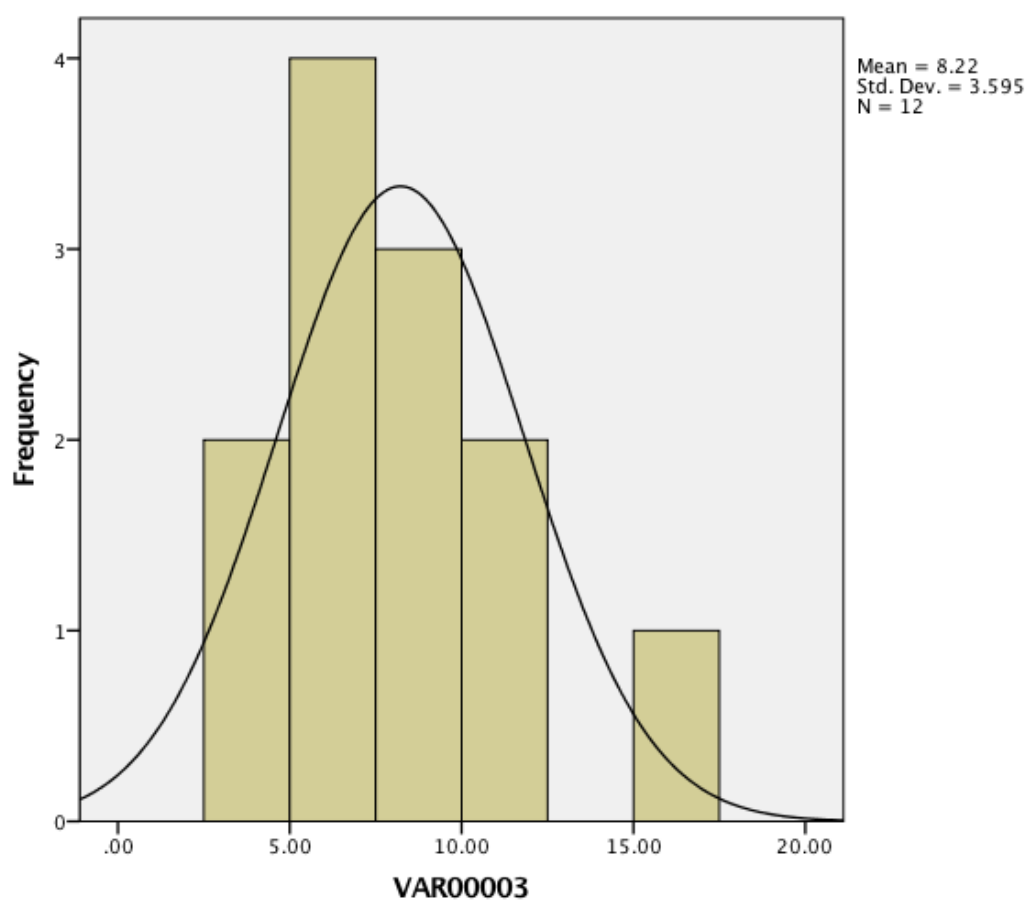
18/18 (100%) responded Yes

#### **8.7.8 Q8. Given the chance would you undergo the same treatment again?**

18/18 (100%) responded Yes

### 8.7.9 Stage 2. Quantitative Outcomes.

Patient's re-innervated force outcomes (as measured with a continuous measure of Kilogram Force; KgF, with a HHD) were normally distributed (mean = 8.2KgF SD = 3.6).



**Figure 8.23:**

Histogram of the spread of objectively assessed force (KgF) as measured with a HHD. Line of best fit depicting MRC Grade 4 subset distribution. Mean 7.2 kgf (3 to 15.5; SD 3.3). (Best fit line as calculated by SPSS software)

Correlations										
		peakforceobj ective	current function	hope	minimal	expect	SPONEA	improvement	difference	Expectation mismatch
peakforceobjective	Pearson Correlation	1	.542	.240	-.433	.380	.631*	.694*	.488	.477
	Sig. (2-tailed)		.069	.453	.160	.279	.028	.012	.108	.164
	N	12	12	12	12	10	12	12	12	10
current function	Pearson Correlation	.542	1	-.083	-.090	-.009	.604**	.573*	.619**	.817**
	Sig. (2-tailed)	.069		.744	.721	.973	.008	.013	.006	.004
	N	12	18	18	18	16	18	18	18	10
hope	Pearson Correlation	.240	-.083	1	.590**	.605*	.324	-.123	-.177	-.267
	Sig. (2-tailed)	.453	.744		.010	.013	.189	.627	.483	.456
	N	12	18	18	18	16	18	18	18	10
minimal	Pearson Correlation	-.433	-.090	.590**	1	.069	.096	-.313	-.157	-.156
	Sig. (2-tailed)	.160	.721	.010		.801	.705	.206	.533	.668
	N	12	18	18	18	16	18	18	18	10
expect	Pearson Correlation	.380	-.009	.605*	.069	1	.275	-.122	-.227	-.632
	Sig. (2-tailed)	.279	.973	.013	.801		.303	.653	.397	.050
	N	10	16	16	16	16	16	16	16	10
SPONEA	Pearson Correlation	.631*	.604**	.324	.096	.275	1	.519*	.560*	.434
	Sig. (2-tailed)	.028	.008	.189	.705	.303		.027	.016	.210
	N	12	18	18	18	16	18	18	18	10
improvement	Pearson Correlation	.694*	.573*	-.123	-.313	-.122	.519*	1	.889**	.753*
	Sig. (2-tailed)	.012	.013	.627	.206	.653	.027		.000	.012
	N	12	18	18	18	16	18	18	18	10
difference	Pearson Correlation	.488	.619**	-.177	-.157	-.227	.560*	.889**	1	.749*
	Sig. (2-tailed)	.108	.006	.483	.533	.397	.016	.000		.013
	N	12	18	18	18	16	18	18	18	10
Expectation mismatch	Pearson Correlation	.477	.817**	-.267	-.156	-.632	.434	.753*	.749*	1
	Sig. (2-tailed)	.164	.004	.456	.668	.050	.210	.012	.013	
	N	10	10	10	10	10	10	10	10	10

\*. Correlation is significant at the 0.05 level (2-tailed).

\*\*. Correlation is significant at the 0.01 level (2-tailed).

**Figure 8.24:**

Table demonstrating multi input bi-variate analysis of two tailed significance of Pearsons correlation

When subjective outcomes are compared to Maximal Peak Force (MPF) there is poor correlation between the majority of the qualitative data and the quantitative outcome. However, there was a link between two of the subjective assessments and peak force, but neither had a very strong correlation ( $r = 0.631$  and  $0.694$ ) Figure 8.24.

- Improvement/impression of change (Q5) had a correlation of 0.694 at a significance level of 0.12

- The SPONEA (Q4) correlated to a similar level (0.631) with a higher significance of 0.028.

The strongest correlations within the collective of subjective assessments were between:

- Hope (Q2.) showed a correlation of 0.59 (at a sig of 0.01) with minimal expectation
- The SPONEA Q4 correlated with several measures as well as the peak objective force:
  - Current function: 0.604 at the 0.008 level.
  - Assessment of improvement (Q5.): (0.519 sig 0.27)
  - Impression of impact/difference (Q6.): (0.560 sig 0.16)
- Assessment of Improvement (Q5) and the assessment of the difference this made (Q6) correlate to 0.889 (with a significance of 0.000)
- Expectation mismatch (\*EM) (Q123) and current function; (0.817 sig 0.004) but, as EM is a derivative of current function, (current function – expectation = EM) this may be likely a product of the relationship rather than demonstrate a causal relationship.

The findings therefore enable us to reject the null hypothesis. The results demonstrate that satisfaction with nerve transfer surgery for elbow reanimation is unrelated to the peak force attainment.

This study demonstrates that the patient related impact of restoring active elbow flexion is unrelated to the amount of force restored. However, the subjective satisfaction for Oberlin nerve transfer is high across the range in force (8.22Kg SD 3.595).

There is a disparity seen between the standard objective outcome assessment of muscle function (as assessed by clinicians) compared to the objective experience and patient's perception of the strength and use of their arm. Peak force is not a responsive or representative outcome

measure to reflect the patient experience of muscle re-innervation. This reinforces that the objective assessment of peak force is not reflective of the breadth of subjective factors that influence a patient's perception of their outcome. However, the study does indicate that maximal peak force does show some correlation with the patient's impression of change and some improvement in function. Patients do not appear to relate peak power in an unrelated or unqualified way to their outcome

## **8.8 Discussion**

This study aimed to evaluate the patient's perspective of their return of muscle function following Oberlin nerve transfer. To the authors' knowledge this is the first study to do this. The standard outcome for this operation has been peak force and these data suggest this is a poor measure of outcome with little validity to patient experience.

Patient reported outcomes are growing in popularity and the strengths and weaknesses of these are well discussed. In designing this battery of questions a multidimensional approach was used in order to try to be as reflective of the many layers and aspects of patient experience as possible. Health Transition Questions (HTQs) do this by directly asking patients to assess whether they consider their health or functioning to have changed in comparison with a previous time point, often pre intervention, pre surgical intervention. Particularly when short measures are employed or single global questions are grouped with HTQs that probe experiences of adverse events or side effects. For example, to assess the accuracy and sensitivity of measures designed to specifically probe PROs in Orthopaedic surgery, treatment satisfaction questions have been posed alongside direct HTQs as an external anchor (Dawson et al. 2008; 2014).

In a recent review (Lloyd et al. 2014) suggest that there are a number of benefits associated with combining a simple set of questions to elicit patients' assessments of the outcomes of hospital

treatment. Most importantly, it directly identifies outcomes relevant to the individual patient, which can differ between patients and also from what clinicians believe to be important to measure. The results of surveys using this type of question may feed into improvements in clinical practice more easily. There is also evidence in the literature that asking patients to assess the outcome of their treatment has face validity. Indeed, Jaeschke et al. (1989) concluded that in the absence of a gold standard measure external global ratings represent a credible meaning of change in a new measure. This is shown in the widespread use of such questions, particularly transition questions as external anchors to assess the performance of other PROMs. This methodology allows identification of outcomes relevant to the patient. Dawson et al. (2010) found that patient satisfaction with surgery poorly correlated with clinician ratings at follow up, and therefore provided more evidence of the difference between patients' and clinicians' perceptions of which aspect of outcome to rate as important (Jenkinson et al. 2002; Wright et al. 1994).

In designing the questions for our data collection tool we utilised a spread of question type, methodology and subject areas. We combined closely defined parameter questions and Likert methods; to bring together investigations on subjective measures of expectation, attainment, function and satisfaction. It has been shown that, questions that interrogate patients as to the extent to which an intervention has helped improve their health, or that explore the direct experience of treatment may be less subject to bias than satisfaction questions (Pathak 1981) Likert-type satisfaction rating scales provide a high degree of precision (Fitzpatrick et al. 1998). It is also known that in order to avoid the problems of using a single global measure which is likely to reflect numerous features of the treatment received, and be closely related to the quality of the care received- satisfaction and assessment of the outcomes of treatment should be measured multi-dimensionally (Cleary & McNeil 1988). In addition, multi-item scales generally yield more score variability, and higher reliability and validity score than single items measures (Ware et al. 1978).

In selecting our anchor objective assessment we rely on our previous work which identified the use of a hand held dynamometer (HHD) as reliable method to measure peak force of elbow strength in this cohort (Quick et al. 2016, Maricq et al. 2014). A previously published pilot study outlined the protocol for use and discusses its weakness (Quick et al. 2016).

A cohort of patients was identified who met the inclusion criteria. They had undergone nerve transfer surgery and successfully gained reanimated elbow flexion to MRC grade IV at 24 months post operatively. A mixed-methods approach was adopted as it seemed best suited to provide a holistic overview and gain the maximum amount of information to answer the research question.

Stage 1 of the study utilised a structured questionnaire to provide insight into patient experience, expectations and satisfaction levels with surgical outcome. Several aspects of the qualitative information were of particular interest:

Firstly, in asking patients to assess their current function (when they had been selected as being able to lift some weight) only 14/18 (78%) identified that the restoration of innervation to the elbow flexors has allowed them to lift some weight (this corresponds with at least MRC grade IV classification). Thus; 4/18 (22%) failed to recognise the functional ability of their reinnervated muscle.

A literature review to identify experience in assessing subjectively rated force (in PubMed and Google Scholar) for the strings ("Muscle strength" AND "subjective assessment") and ("Muscle power" AND "subjective assessment") ("Muscle power" AND "patients assessment") ("Muscle force" AND "experience") ("Muscle assessment" AND "experience") ("Muscle assessment" AND "subjective" AND "objective") identified no pertinent studies.

The authors' discussions with colleagues identified a systematic review on shoulder outcome named "Patient reports of the outcomes of treatment: a structured review of approaches" by Lloyd (2014) highlighted, as one of its themes, force assessment in shoulder outcomes. From

here two studies were identified which showed assessment of force (Smith et al. 2006; Yang et al. 2015)

Yang (Yang et al. 2015) identified one hundred and twenty consecutive patients at their 1-year postoperative visit after shoulder arthroplasty and captured patient assessed, home-based questionnaire. Within this study the patients lifted bags filled with water up to a mean weight of 2.72Kg. This test was designed to test range of motion under differing loads not peak force.

Smith (Smith et al. 2006) assessed that “*physicians rated ... strength as being closer to normal* [in comparison with the subjective assessment]”. This study was an assessment of a consecutive series of 68 patients encounters who were at the point of assessment at an average of 51 months following shoulder surgery (range 6 months – 22 years). The assessment was framed as a rating of ‘the overall strength of the shoulder’ and was graded with a 10 point Likert scale (with non linear ‘advisory statements’) such as from normal was 1, Good- 3, Fair- 4.5, Poor 6.5, very poor – 8 and Paralysis – 10.

***Please rate the overall strength of the shoulder:***

Normal		Good		Fair		Poor		Very poor		Paralysis
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
1	2	3	4	5	6	7	8	9	10	

They had patients complete this assessment by colouring in a circle and a similar assessment was preformed by the treating surgeon or one of the junior medical staff. The two groups graded the force – physicians 3.75 +/- 2.3 and the patients 4.43 +/- 2.3. The mean difference is assessed as being -0.68 with the 95% intervals as being -1.12 and -.025).

This does appear to be an area of research which will require more attention. It is however important not just to assess what the disparity is between subjective and objective assessment of force (as shown in graph x) but to investigate why. These data have shown an overall pessimistic



assessment of elbow flexion assessment both in terms of global MRC (anchored statement scale) and the KgF (anchored statement scale). This may represent a lack of internal validity of the measure- that the cohort do not fully understand how to assess their elbow flexion force, but it is considered that it more likely represents that muscle peak force is not a quantity which represents patient experience.

When patients were asked to disclose their realistic expectation of surgery (Q2) 78% reported an expected outcome of MRC  $\geq 4/5$ . As previously discussed, the published data regarding the outcome of Oberlin transfer in terms of peak force is considered to be MRC grade IV in an average of 80% of cases (Sedain et al. 2011; Goubier & Teboul 2007; Ray et al. 2011). This suggests that the expectations of patients with regards to their likely outcome are being well met. Furthermore, it may act as an indicator that patients have been appropriately informed during the consent process with realistic outcomes portrayed. It is interesting to note that patient expectations are closely associated with their ratings of satisfaction with medical care (Kravitz 2016; Williams et al. 1995) and it may be an effect of treatment in a specialist centre that the patient cohort receives multimodal education and a common message to prepare expectations.

The inclusion criteria of the study purposely selected individuals who had documented recovery of at least grade IV elbow flexion. Conversely, 4/18 (22%) participants reported that the return of power was insufficient for them to lift weight. Furthermore, one respondent reported that they were unable to bend their elbow without assistance. This demonstrates some conflict with the clinical documented outcome of grade IV MRC. There is the possibility that these outliers may have misunderstood the nature of the question. Equally their answers display the potential mismatch between clinical assessment of force and patient perception of outcome. In order to assess the demonstrated variance between the predicted and observed force for the Q3b it is noted that there have strangely been few studies to assess patient's assessment of their own force as above. Several questions highlighted that it is not just the recovery of elbow flexion

force that is important to the patient. This is illustrated keenly in the free text responses only two patients use the word 'elbow' the vast majority refer to their 'arm' as a wider assessment.

Question 4 focussed on the SPONEA which was an adaptation of the SPONSA. The SPONSA – the Validation of the Stanmore percentage of normal shoulder assessment is a validated outcome measure (Noorani et al. 2012) for shoulder function now widely used (George, Malal et al. 2014, Torrance et al. 2017). Our modification is asking the same question “A normal shoulder is one which is pain-free, with a full range of movement, normal strength and stability, and allows you to do what you feel your shoulder, if normal, should allow you to do. A normal shoulder is scored as 100 percent, while a completely useless shoulder is scored as 0 percent. Overall where would you rate your shoulder between 0 and 100 percent, at this present time” but replacing the word shoulder for elbow. This a novel subjective measure of elbow function introduced specifically for this study and whilst it takes face validity from the SPONSA it is not yet formally fully validated. However, the SPONEA was able to demonstrate a significant correlation with Maximal Peak Force (two tailed significance  $p= 0.008$ ) suggesting that it may have some clinical utility as an assessment tool. This is not a surprise though as integral to the question is a concept of 'normal strength' and thus it would be expected to be reactive to differences in the force of elbow flexion. Further studies are required to validate its use but this may be a valid tool to assess outcomes for the Oberlin.

Most patients reported that the surgery had made a worthwhile or huge difference to their life with 16/18 (89%) rating it as providing a 4/5 or 5/5 difference to their lives. Patient satisfaction is perhaps the most important criterion of success. This concept is well recognised in the service industries, though remains something of a nebulous concept in clinical care (Hamilton et al. 2013). Patient reported outcomes measures (PROM) difference reporting for many orthopaedic musculoskeletal procedures have high ratings and varicose vein and breast reduction surgery.

In a large cohort (n=4709) of prospectively followed cohort with 95% take up Hamilton (Hamilton et al. 2013) patients were also asked to rate their overall satisfaction with their operated hip or knee on a four-point scale (very satisfied, satisfied, unsure or dissatisfied). Data on satisfaction with five specific facets of surgical outcome were obtained with the following questions, answered on a six-point scale (excellently, very well, well, fairly, poorly, don't know): (1) 'How well did the surgery relieve the pain in your affected joint?'; (2) 'How well did the surgery increase your ability to perform regular activities?'; (3) 'How well did the surgery allow you to perform heavy work or sport activities?'; (4) 'How well did the surgery meet your expectations?' We then asked our patients to indicate their satisfaction with the care they received at the hospital with the question (5) 'rate your overall hospital experience' using the response scale; excellent, very good, good, fair, poor or unknown. We also asked further two questions that enquired as to the patient's attitude towards further surgery: (1) 'Would you have this operation again if it were required on another joint?' and (2) 'Would you recommend this operation to someone else?' (Possible responses: definitely yes, possibly yes, probably not, certainly not or not sure) Overall patient satisfaction was predicted by: (1) meeting preoperative expectations (OR 2.62 (95% CI 2.24 to 3.07)), (2) satisfaction with pain relief (2.40 (2.00 to 2.87)), (3) satisfaction with the hospital experience (1.7 (1.45 to 1.91)), (4) 12 months (1.08 (1.05 to 1.10)) and (5) preoperative (0.95 (0.93 to 0.97)) Oxford scores. These five factors contributed to a model able to correctly predict 97% of the variation in overall patient satisfaction response.

The two final questions focussed on satisfaction in the context of whether the patient would undergo the same procedure again and whether they would recommend it to someone else. 100% of respondents said yes to both. The answers to these questions demonstrate the subjective impression of the impact of the surgery. When reviewed alongside the free text answers to Question 6 the strong positive results can be visualised. Several participants' report that their arm was "useless" prior to surgery and many comments also focus on a return to "function" or "semi-function" within the arm. Furthermore one participant reported that they get comfort from

being able to grasp and lift light items. It may be surmised that in cases of life changing injury, satisfaction or impression of change tools may not be sensitive to the multidimensional and biopsychosocial effects of injury and therefore struggle to guide improvements in outcome measurement. Stage 2 of the study was to compare the most commonly used current assessment technique (of maximal peak force) correlated with the information gained in stage 1. The results again correlated with other literature (Quick et al. 2016; Carlsen et al. 2011) with an average of 8.2KgF (SD 3.6). When compared to the findings of Stage 1 and when considered in relation to the research question maximal peak force does demonstrate some face validity to the patient as an outcome measure; but only as part of a much more complicated picture. The findings of this study indicate that patients determine the impact of an intervention by how much they feel they are able to do. When the answers from the questions regarding what difference the surgery had made to their lives were compared to actual force outcome there was no significant correlation (0.488 with a non-significant level of evidence  $p = 0.108$ ).

## **8.9 Study limitations**

There are various limitations within this study. Firstly, assessment of self reported function was solely focussed on motor recovery. Although recognised as important considerations for holistic management; Features such as Quality of life (QoL), pain and body image were not incorporated. This streamlined the study and reduced the scope of the commentary limiting the possibility of the full breadth of subjective experience from being expressed.

The retrospective nature of the study is not ideal; it was conceived as a pilot to inform the design of future prospective data capture studies. A 30% (18/62) follow up rate undoubtedly raises concerns of outcome bias however this response rate for trauma patient follow up is quite usual and representative of a typical trauma population (Leukhardt et al. 2010; Crandall et al. 2014). Commonly cited difficulties when arranging long term follow up with this cohort typically refer to

patients who are young, mobile and wish to return to normal life. Future studies may be advised to establish prospective data collection methods to enhance follow up rates.

Patients were given the opportunity to remain anonymous or disclose their identity when completing the questionnaire. All participants chose to discard anonymity. In order to avoid any further bias the researchers ensured that any treating clinicians were absent during the data collection process and that the entry of data was not overseen.

Finally, this study adapted the wording from the SPONSA (a validated shoulder assessment) to create an elbow specific SPONEA. Although the SPONSA has been shown to be a legitimate measure for use with shoulder patients. It has not yet been assessed if it will have the same validity when modified for different joints (Noorani et al. 2012). However, the findings of this study suggest that the SPONEA may be a useful indicator of patient reported outcome for elbow reanimation. Considering the results of this investigation, future studies to validate the use of the SPONEA are recommended.

## **8.10 Conclusion**

In summary, muscle is a complex organ and its functions beyond strength alone should be considered during assessment of outcome following a denervated period. Proprioception, functional co-contraction and mechanisms of smooth and controllable recruit-ability are some of a myriad of aspects of muscle reinnervated function which have been identified as limiting factors to recovery post injury. Asking the patient's opinions with regards to outcomes will enable clinicians to specifically measure valid improvements that exceed the minimal clinically important difference for that outcome. If we are to, quite acceptably, use peak power to inform studies on outcome it should be with one eye to the other dimensions of muscle function and global patient function. The results of this study have provided insight into the spectrum of motor outcomes. Ongoing

studies of a qualitative nature such as focus group discussions are recommended to further direct care.

## 9.

# **The lived experience of motor recovery of elbow flexion via nerve transfer.**

A phenomenological analysis of a group discussion around the experiential learning from living through motor recovery.

### **9.1 Introduction**

Nerve injuries to the upper trunk, lateral cord and musculocutaneous nerve can all result in the loss of active biceps contraction. Surgeries such as nerve repair, grafting or nerve transfer are often required to allow axonal regrowth into the de-innervated muscle. Loss of active elbow flexion creates a considerable deficit in function. Activities such as hand to mouth for feeding and hand to the midline to allow for independent dressing are commonly reported functional goals. Despite best efforts from both the surgical and therapeutic teams these injuries often result in long-term functional disabilities which affect all aspects of daily living.

To date, no research has focused solely on the qualitative lived experience of motor recovery following a nerve injury. The purpose of this study was to give an account through the voice of patients' who have successfully undergone nerve transfer surgery to re-innervate elbow flexors. It is hoped that the thoughts and feelings of these patients can facilitate medical professionals to better understand these life-changing injuries; leading to improvements in patient care.

The aim of the research was to explore the opinions of those who have suffered a nerve injury with successful re-innervation of elbow flexion following an Oberlin nerve transfer. Phenomenological analysis of focus group discussion was identified as a suitable method to fulfil this aim and capture the participants' lived experience.

Traditionally health research has put great emphasis on quantitative studies which focus on outcome of injury to determine the efficacy and effectiveness of interventions.

This is most likely born from the much quoted pyramid hierarchy of “best evidence” being focused towards Randomised controlled trials (RCTs) and systematic reviews (SR) (Evans 2003). Success is typically judged on elements such as isolated return of strength to a muscle; rather than the wider aspects of how that enables the person to participate in life with regards to family roles, employment and hobbies. Therefore, these closed traditional methodologically quantitative outcome studies do not provide information to explore the themes of how to assess or improve the experience of patients living with brachial plexus injuries.

Modern healthcare is increasingly recognising the need to move away from a traditional medical approach and focus towards a bio-psychosocial approach. In essence putting the patients experience as the focus of all that we do. The World Health Organisation (WHO) developed the International Classification of Functioning, Disability and Health (ICF) as a framework for measuring health and disability at both an individual and population level (WHO, 2001). In this framework both the muscle function and the person’s perceptions are considered alongside their ability to participate in everyday activities. This reflects the recent changes in healthcare where patient perceptions and satisfaction are considered with equal status to a clinician’s “objective” outcome. Recent analysis of outcome following nerve injury has endorsed the use of patient-reported outcomes and functional assessments (Novak et al. 2009; Ahmed-Labib et al. 2007; Kitajima et al. 2006).

Choi et al. (Choi et al. 1997) used a quantitative questionnaire survey to evaluate surgical treatment for brachial plexus injury (BPI). The main outcome measures were overall life satisfaction, employment, and functional outcome. In spite of the devastating nature of their injuries, their patient population reported a good quality of life and employment within the first year following injury. Davidson (Davidson 2009) compared upper limb amputees and patients with upper limb



injuries using the Disability of the Arm, Shoulder and Hand (DASH) questionnaire. She found patients with a BPI demonstrated significantly higher levels of disability compared to patients with unilateral upper limb amputations. However, the study was unable to provide information regarding the person's perceptions of their disability. This study postulated that the definitive nature of an amputation which differs from the somewhat unknown prognosis following BPI may lead to delayed acceptance, and altered views of long term disability.

More recently Kitajima et al. (2006) conducted a quality of life (QoL) study for patients who had suffered a BPI. They found little correlation between SF-36 scores and clinical evaluation of joint function. This led them to conclude that a region or site-specific questionnaire is required to better evaluate the outcomes of BPI. In summary, these studies suggest that questionnaire based surveys can offer some information with regards to how a patient is living with an injury. However, they are restricted in the capacity of what they provide. The main limitations are that they generate a defined set of data relating to the direct questions asked rather than providing a deeper understanding of the impact of a nerve injury. They do though offer pieces of this puzzle for analysis.

Further challenges in assessing this group of patients is the heterogeneity of the traumatic injuries and the multi-factorial impact. There is no such thing as a typical traumatic brachial plexus injury (TBPI). For each person with a brachial plexus injury (BPI), the associated injuries, events surrounding the injury, recovery, and life experiences are individual.

Qualitative research aims to understand human experience. Whereby, a person-centred and holistic approach interprets and makes sense of phenomena in terms of the meanings people bring to them (Greenhalgh & Taylor 1997). In light of the limitations identified by quantitative studies in BPI; this paradigm is appears particularly well suited to understanding the patient's own experiences and puts them at the centre of the study. There have been two previous studies focussing

on the lived experience of brachial plexus injuries. Wellington (Wellington 2010) used semi-structured interviews focussing on QoL issues following BPI. Her study centred around four subjective experiences that the participants had identified as being significant following their BPI: employment, pain, body image and sexuality/emotions. Further to this McDonald and Pettigrew (McDonald & Pettigrew 2014) interviewed patients and used a phenomenological approach to examine the core concepts of the lived experiences of people with this injury. Quality of life, motor function, activities of daily living and societal roles were noted to be key concepts.

Previous research by the author (Chapter 8) has shown that patient satisfaction and impression of benefit following re-innervation of elbow flexors has only a small effect on, and low correlation with the peak force generated (correlation of 0.694 at a significance level of 0.12). As peak power is the main (and often the only) outcome measure used by clinicians to assess this type of procedure. The intention of this research is to direct and inform future research aims towards outcomes that are meaningful to the patient experience.

To date, no research has focused solely on the qualitative lived experience of motor recovery following a nerve injury. The purpose of this study was to give an account through the voice of patients' who have successfully undergone nerve transfer surgery to re-innervate elbow flexion. It is hoped that the thoughts, feelings and experiences of these patients can allow researchers and therapists to learn from the 'lived experiences' to better direct their care and understanding towards these life changing injuries.

## 9.2 Design & Methodology

Mason (Mason 2017) *considers qualitative research to be:*

*“a highly rewarding activity because it engages us with things that matter, in ways that matter”*

This study was designed and reported in accordance with the COREQ guidelines (Consolidated criteria for REporting Qualitative research). A checklist is provided as an appendix (Tong et al. 2007).

### 9.2.1 Overall Approach and rationale

The aims of the research were to explore the opinions of those who have a lived experience of a nerve injury with the successful return of power to elbow flexion following an Oberlin nerve transfer. In order to complete this aim a qualitative methodology was identified as an ideal method to capture participants' lived experience.

A broad range of qualitative methodologies exist. The four most commonly used methodologies include Grounded Theory, Phenomenology, Ethnography and Narrative research (Creswell & Poth 2016; Petty, Thomson & Stew 2012a). The methodology selected should depend upon what the research aims to gain from the participants.

The purpose of this study was to focus on the patient's voice; to ascertain what the motor recovery of their biceps meant to them. The information gained was intended to reflect as many people's views as possible; so as to be transferrable to other patient's in a similar position but still maintain the essence of what each individual had said. This directed the study design away from a grounded theory of qualitative study and towards a phenomenological approach. The focus of Phenomenology is to understanding the unique lived experience of individuals by

exploring the meaning of a phenomenon. Interpretation and analysis of the data enables the researcher to uncover a description of the 'essence' of the phenomenon also described as "the universal meaning for individuals" (Petty, Thomson & Stew 2012a; Petty, Thomson & Stew 2012b).

### **9.3 Patient-Participants**

Patients under the care of the Royal National Orthopaedic Hospital Nerve Injury Unit were assessed for the inclusion criteria: Participants had: a diagnosis of Traumatic brachial plexus injury and had undergone a nerve transfer to reanimate a denervated elbow flexor muscle, who had follow up of over 24 months post surgery. (All participants were over 2 years post operation to allow a suitable time to have elapsed for the experience of motor recovery to be present and the key features of their lived experience to still be memorable). Selection inclusion criteria: the patients had to be over 18 years of age; speak fluent English; and be able to participate verbally with the process. Participants were excluded from the study if they had: birth-related BPI; were less than 24 months post nerve transfer; had impaired cognitive functioning; or had difficulties in verbal communication. This yielded a cohort of 68 patients. Patients were approached and invited via letter to be involved in the research. (with consent to do so from our institutions research ethics board) via written letter and a single follow up phone call for non-responders.

This project was approved by a national research and ethics board:

**REC ref 16/LO/0623**

**IRAS project 202847**

A group of 23 patients was recruited in this manner to engage in a qualitative research project to quantify their reinnervated motor function. Of this group all were invited to participate in a group

discussion on the experience of motor recovery. Subsequently a group of 6 patients of varied backgrounds and times from injury to surgery (see Figure 9.1) consented to attend.

Identifier	Age	Time since injury	Gender
GP	47	42 months	M
JT	46	29 months	F
PA	45	45 months	M
LJ	28	29 months	M
TB	54	260 months	M
SB	37	28 months	M

**Figure 9.1:**  
Patient participant demographics

#### **9.4 Data gathering methods**

A research team was established with the author and two therapy colleagues; an OT (KJ) and a Physiotherapist (HB). The details of this team are included in the section on researchers below. The research team worked together in this area to develop a robust methodology towards the aim of establishing a lived experience of muscle re-innervated from nerve transfer process as collaborative, emphasising that the participants were the “primary experts”

The discussion group was thus established and was chaired by one health care professional (KJ) who had been uninvolved in the clinical care of the 6 participants and had no previous relationship with the individuals. The discussion was observed by another therapist (HB) whose role it was to passively observe the interaction of the group to enhance analysis.

The author and lead researcher (TQ) excluded himself from the group discussion as he was the treating surgeon for a number of the patient participants and reporting bias was feared in his presence. A multidirectional digital voice recorder was used to record the hour long process which was held on NHS property in a non-clinical area. The audio file was later typed to create a transcript for use during the analysis. Once received, the transcript was reviewed by KJ and HB and corrections made to certify verbatim.

## **9.5 Data analysis methods**

The intention of the study was to gain an insight into the “textured life-world” of patients and their evolving values as they grapple with disability (Greenfield & Jensen 2010).

Two researchers (HB and TQ) analysed the data. TQ; being the external observer, and HB; immersed in the group. HB was able to refer to the nuances and observed preferences of the group which may not be inferred from the transcript and audio file alone.

Both the recorded audio file and the transcript were repeatedly reviewed, as were the notes and commentary written by HB during the group session. The researchers individually coded the discussion and highlighting the significant statements from the transcript. This method of data analysis is endorsed by Colaizzi (1978) as a method of maintaining the voice of the participants throughout. Following this, the researchers then met to discuss their individual impressions. Their professional backgrounds and roles within healthcare were declared as part of an effort towards conscious reflexivity. Following this; agreement and disagreements regarding the significant statements were discussed. The ideal of maintaining the ‘patient voice’ in the subsequent

analysis was always conformed to. Phenomenological processes, using a framework content type analysis were used in a step wise, manner to arrive at a 'structure of understanding'.

An independent fourth researcher (AG) who was naive to the subject area but who has experience in qualitative research methodology was asked to review the process, codes and themes in order to assist with transferability and accuracy.

## **9.6 Researchers**

- Tom Quick (TQ) MA(Cantab) MB FRCS(TR&Orth) FHEA is a Consultant Peripheral Nerve Surgeon at the Royal National Orthopaedic Hospital (RNOH) and Director of the Peripheral Nerve Injury Research Unit (PNIRU). His sole clinical focus is the treatment and reconstruction of nerve injury, mainly brachial plexus injuries in children, adolescents and adults.
- Hazel Brown (HB) MSc, BSc, Dip Orth is a Highly Specialised Physiotherapist treating adult and paediatric nerve injured patients at the RNOH. She has a wide experience of qualitative and quantitative research methodologies and outcome assessment validation.
- Kathryn Johnson (KJ) Dip Phys is a Clinical Specialist Occupational Therapist who has worked with nerve injury patients for over 10 years. She has a wide experience of service development and patient advocacy.
- Anthony Gilbert (AG) MRes, BSc is the Therapies Research Coordinator and Orthopaedic Physiotherapist at the RNOH. Anthony has significant clinical and academic experience in designing and delivering qualitative research methodologies.

All researchers have received Good clinical practice (GCP) certification from the National Institute of Health Research (NIHR) and maintain good standing with their professional bodies.

## **9.7 Reflexivity**

Reflexivity is the important process of stating and recognising the continuum of research identity, voice and biases, within phenomenology. Thus in order to ensure this analysis was well grounded within its reflexivity: The two researchers involved in the analysis (HB and TQ) expressly and formally reflected their own identity, sense of voice, perspectives, assumptions, and sensitivities (as set out p.96 Marshall & Rossman 2011). Furthermore, the two analysing researchers undertook a group activity to identify the expressed subjective and objective differences between their two expressions of self.

## **9.8 Ethics**

Ethical approval was granted by our institutional ethics board to convene the group discussion and to record and analyse the discussion as part of a wider project to explore patient assessed outcomes in renovated muscle. All participants were assured that their participation was voluntary and could be withdrawn at any point and any decision to enter or leave the trial would not change or affect the care they received.

## **9.9 Data Collection**

This discussion was held on NHS Hospital property and was chaired by a senior therapist who had no previous engagement with the patients (KJ) and observed by another senior independent therapist (HB). A group of six patient-participants were invited to share their experiences around



the process of “return of function of their elbow movement”, all six attended. The restored function (of active elbow flexion) was identified to the whole group via a picture, so as to frame the discussion with all commencing with a shared starting point. The whole process was recorded with consent from all involved to a digital audio recorder. The process was approved by the clinical ethical review board of our institution

Two researchers (TQ and HB) then analysed the hour long discussion separately. Each researcher listened to the audio file numerous times and the transcript read and re-read to get a sense of the whole. Through this process the two researchers were able to attend to both the verbal and non-verbal elements. The researchers allowed the appreciation of the the non verbal assessment (including subtle pauses, intonation and emphasis) to inform the reading of the transcript.

Following this repeated and considered immersion in the discussion each researcher highlighted on a digital copy of the transcript fragments that represented text that (to that researcher’s opinion) represented an aspect of ‘what this experience is like’. These ‘significant statements’ were then shared between the two researchers and over two discussions these were explored. Following the process of the Colaizzi method (Colaizzi 1978, Sanders 2014) these significant statements were then carefully considered again to determine a sense of its meaning. These were then again brought to group discussion where bracketing was performed recognising the varied reflexivity of the two researchers differing character, experience, training and personality.

These formulated meanings were then combined in to themes and then further clustered into groups. These theme clusters were again analysed to identify emergent themes- which were characterised by a identification of statement (in the patient-participants own words as a direct quote from the transcript) which the researchers agreed represented a valid and candid

expression of the emergent theme. Thus we returned, in our final stage of this analysis, to the direct truth contained in the patient-participants' own words.

## **9.10 Summary**

This study has been a inductive phenomenological analysis arrived at through a process of theming and coding (after Colaizzi 1978) of a group discussion [transcript attached as an appendix] between a varied group of six patients who were invited to talk on their views and experience on living through motor reservation of elbow flexion following nerve transfer.

As part of the process of integration of the Royal National Orthopaedic Hospital Peripheral Nerve Injury Unit's (RNOH PNI) clinical and basic science research projects the team wished the patient voice to be central to the direction of study. There is now a wealth of phenomenological study in healthcare which has informed service improvement, training, outcome design and to frame research questions (Starks & Brown Trinidad 2016, Shaw & Connelly 2013, Tanner et al. 2007). Numerous studies have been carried out that report on the functional outcomes following traumatic brachial plexus injury (TBPI), but there is a noticeable lack of qualitative evidence that explores the subjective experiences of people following such an injury. The recent work of the RNOH PNI unit has been in assessing quantitative outcomes from motor recovery and nerve transfer. Assessing this as a discrete and standardisable intervention to renerve essential motor functions. This work has identified that measures deemed valid to the patient body have not been clearly identified. Many qualitative studies have been published measuring maximal peak force following nerve transfer to restore function of elbow flexion (see review of literature in chapter seven) A recent study by this team has shown that peak force is not viewed as valid primary outcome measure.

One of the five major themes identified in Wellington's 2010 study of five men with isolated brachial plexus injuries was that of the impact of lack of movement and muscle bulk on body image and function but also that of specific surgical interventions. This further supports the methodology of selecting a series of nerve transfers and exploring the experience of motor recovery.

This study builds upon this lack of available evidence and introduces the brachial plexus injury patient and investigates their experiences.

## **9.11 Results**

The original recording was sixty-eight minutes long, the transcript 10,279 words long. Significant statements were first identified by each of the researchers (TQ and HB) these were condensed via agreement to a collection of significant statements by consensus agreement. [tabulated data attached as an appendix].

These significant statements after conversion by each researcher to formulated meanings were again considered in discussion and numerous themes were identified and these were further collapsed to four major themes. We present this hierarchy under the headings of the emergent themes.

## **9.12 Findings**

The four primary themes (Figure 9.2) are all extracted from the analysis of 'significant statements' made by the participants during the interview process. The significant statements are grouped into primary themes within which there is a sub-architecture of 'secondary themes'



**Figure 9.2:**

Major themes identified from the phenomenologic analysis of the discussion group.

### **9.13 The complete understanding of pain**

The most commonly raised comments within this discussion on motor recovery were those characterised as relating to pain. All of the patient-respondents produced significant statements that relate the experience of pain within the remit of the recovery of motor function.

This is in line with clinical experience and previous studies which have highlighted pain as a major feature of nerve injury.

*“The complete understanding of pain; I don’t think I thought, or had any concept of what the nerve pain was going to be like” JT*

9.13.1 The severity, nature and intensity of the descriptors of pain varied from an aching sensation

*“what I do suffer with is just a bit of arm ache” TB*

*“I just have like an achiness and that just drains you after so many hours you cant take it you just have to go to sleep” LJ*

Through to accounts of much higher severity:

*“at the start some of the pains were horrendous” PA*

*“sharp shooting pains” SB*

*“Oh my god the pain” JT*

The trend through all participants was for the pain to slowly change from more evaluative words suggestive of difficulty with coping with pain through to more sensory aching type sensations as time progressed.

*“I mean at the start some of the pains were horrendous so much pain there. Then it got better over time” PA*

One participant described the sensation of “fixing pains” in his biceps when he initially felt and saw signs of renervation. Perhaps it could be interpreted as a concept that the body is healing and the surgery will be successful changes patient’s perception, acceptance and tolerance of pain once they see it is for the “greater good”

*"I didn't know if they were fixing pains or if the pain was just there" SB*

The quality of pain that was reported also varied from strange feelings (paraesthesia) through to those of unpleasant feelings (dysthesia).

*"really right elastic band" LT,*

*"fixing pain" SB,*

*"very weird, hypersensitivity" LJ*

*"kind of rubbery." LJ*

*"a real pulling" JT*

*"heavy aches" JT*

*"pins and needles pain" TB*

#### 9.13.2 Evolution & external environment

Pain is an ever changing quantity in the lived experience, with past recollection of pain often being worse than the current reported experience. Patients often reported external influences such as work, weather or just the temporal accumulation of time and daily routine affecting the pain.

*"the pain was horrendous before" JT*

*"still feel kind of rubbery" LJ*

*"I find the pain worse in the cold" SB*

*"but come after a few hours or a tiring day then I get arm ache" TB.*

#### 9.13.3 Impact & Understanding

This relates the associated feature of the pain and ways that the impact of the experience of pain influence the patient's daily life.

*"I just have like an achiness and that just drains you after so many hours you cant take it you just have to go to sleep" JL*

*"that I was in so much pain that at best I could use a pen just couldn't use my arm" TB.*

*"But so much pain there I couldn't actually feel what the movement was and then it got better over time" PA*

Further relating to the experience of pain it is reported that preparedness and education on the likely nature and impact of pain is something that the cohort would consider useful to reduce its impact.

*"The complete understanding of pain; I don't think I thought or had any concept of what the nerve pain was going to be like" JT*

*"Education what actually kind of symptoms I would get and where the pain would be" JT*

The experience of pain shows much commonality that the pain is complex and made up of differing pain. Undoubtedly, aspects of this pain are related to the underlying nerve injury, but also there are elements from the muscle reinnervation process. There is a concept of some pains representing healing processes 'fixing pain' (re-innervation) and others being 'just pain that was there'. There is also the recognition that some of the pains hypersensitivity, parasthesiae and dyesthesiae are related to the nerve transfer surgery donor morbidity.

## **9.14 Patience & positive thought**

The element of time of recovery following nerve injury is so different from other bony or soft tissue recovery courses. This primary theme is picked up by our interlocutors with a number of secondary themes:

### **9.14.1 Hope & expectation**

The 'expectation' is often simple and clear:

*"I just wanted my bicep to work again" JT*

*"I just thought it would be fixed" JT*

*"that was my intention to make sure everything worked again" GP*

but it is also recognised that it can be 'complex, different and personal'.

*"so many different scenarios you could give then person a realistic idea at the start of what they can expect" PA*

*"I don't think I had even thought that it might not be back how it was, I don't think I even had any expectations" JT*

### **9.14.2 Delay- patience and the effect of time**

All agreed however about one thing; 'delay':

*"my bicep didn't look like it was doing anything for ages" GP*

*"patience is needed" TB*

*"and you expect it to not, nothing happened for ages, and then still keeping going and going trying to work the extra little bit" JL*

*"I was very naive thinking next month I will be fine" JL*

*"I was told I was going to have to be patient but I thought I don't think do" JT*



*"I just felt that I could see the progress I was making and the made me more determined to carry on more progressing" GP*

#### 9.14.3 Emotion

The element of emotion demonstrates the impact of restrictions in activity and the effect of pain. This seems by many to be mitigated in some manner by being prepared for the way things will be.

*"if I had done that earlier I might have been less frustrated" JT*

*"yeah and its difficult because pre surgery I just wanted my arm back and I don't think I had any perception about what that would mean afterwards" JT*

*"I was so angry I couldn't take care of myself and that was my thing I wanted to do that"*  
*"TB*

*"didn't think it had worked so I was kind of getting really despondent about it" GP*

Including a progression over time from 'frustration' to 'acceptance'.

*"bit of a roller coaster ride" TB*

*"I was so angry I couldn't take care of myself and I that was my thing I wanted to do that"*  
*TB*

Also that this was variable between individuals

*"I wasn't really concerned about or hadn't even thought what that would mean post-surgery. I just wanted my bicep to work again" TB*

*“you are not going to be training everything else depends on the level of the injury but the important thing is to motivate people correctly at the start and give them some realistic expectation and motivation” PA*

## **9.15 Functionality & daily lifestyle**

The patient voice is very clear that function is about activities of daily living (ADLs). The ability to care for one’s self, for reason of function, of independence and of self respect are repeatedly seen.

9.15.1 ADLs (activities of daily living) feature as clear markers of function and metrics for rehabilitation:

### **Perception of function**

*“You can do what you want to do but you are doing it in a different way” SB*

*“I think general day to day life, so like job side of things- getting the kettle, getting the dishes done, brushing your teeth anything like general living if you did functionality like that “LJ*

*“any function is better than non so the is kind of just the starting point” SB*

### **Functional goals**

*“everybody’s goals are different because of lifestyle and all injuries are different” SB*

*“because some people will have unrealistic expectations everyone different.” PA*

*“just to move it was a reasonable outcome” PA*

*“one of my goals was that i could wash and dress” GP*

*“being able to drive was the first milestone one for me” LJ*

## Being normal

*"my ultimate goal is always that nobody that doesn't know me would know that I have got an*

*injury" GP*

*"what I wanted was just to be able to go to the loo and take care of myself" TB*

## 9.15.2 Coping

There are many methods described as hope to best cope with the impairments experienced:

### Forced use

*"I make a really conscious effort to use my weaker arm far more than I would have done previously it is not my natural arm to use" GP*

### Strategies for use

'Compensation' or adaptation are oft-discussed strategies to attain function.

*"You can do what you want to do but you are doing it in a different way" SB*

*"if I am taking something down from somewhere I will get so far then I will change my tactics" TB*

*"I learned how to do everything left handed so I didn't have to rely upon it or anybody" GP*

### As is the technique of avoidance

*"I have got used to opening doors using hips, bum foot everything I use now rather than use my right arm" JT*

### 9.15.3 Fatigue and Tiredness

Closely linked with the performance of ADLs was the concept of fatigue and tiredness impacting on their ability to carry out activities.

*“I think repetitive tasks are difficult” GP*

*“holding the phone using the phone for any length of time” GP*

When completing most other tasks there is a ‘tiring function’ issue

*“after 10/15 minutes of using the mouse my arm is absolutely knackered” TB*

*“and uncomfortable by Friday just lifting the arm on Friday is just exhausting” JT*

*“I think repetitive tasks are difficult” GP*

As is the experience in rehabilitation from any major trauma ‘general tiredness’ also features as a separate secondary theme

*“sometimes I get a bit tired but you just do it but my life visually is quite normal” TB*

*“what is the actual fatigue and what is the meds” PA*

## 9.16 Don’t call me a Biceps

This primary theme taken from a patient participant statement (*“It is not measured as a bicep as it doesn’t work as a bicep, you cant call it a bicep” TB* ). This means that even though the elbow flexors have been re-innervated and are again able to volitionally contract they are not restored to full function- Thus as they are not acting fully as a biceps they should not be called a biceps.

It is an exploration of the specific experience of recovering and putting reinnervated muscle function to use. This starts from a position of not just functional loss but ‘body image impairment’ too:

#### 9.16.1 Body image

The importance of self esteem and not just as relating to functional loss of the arm but ‘body image impairment’ also was raised within the discussion.

*“it was completely wasted away” SB*

*“yeah its vain but when you talk about looks you see it come back you can see the atrophy” JT*

*“my ultimate goal is always that nobody that doesn’t know me would know that I have got an injury” GP*

The most simple characterisation of the lived experience following nerve transfer to elbow flexion can be described by this ‘significant statement’:

*“It is not measured as a bicep as it doesn’t work as a bicep” TB*

Our patient-participants consider the function of being a muscle as much more than offer just strength of contraction; A muscle should provide in all aspects of life, restore function, without fatiguing, feeling normal, easily controllable, without pain and look normal.

### 9.16.2 First initiation of movement and control

There is a common timeline of experience as regards the process of re-innervation. The processes detailed above relate to the worry and concern regarding the time lag to return of function. The point where this period of waiting is terminated is reported as a momentous experience.

Following surgery and after a long wait the 'rehabilitation experience' is the euphoria of activating the newly reinnervated muscle

*"it was the best feeling in the world when you see it move" PA*

*"It made sense then that everything was going to work again." GP*

During this process of learning to control the returned function it was noted that the support of biofeedback programme and hydrotherapy were greatly valued:

Bio-feedback: a process of supporting conscious awareness of which muscle are firing, (as this can often be difficult to directly sense). It often works through multi-sensory feedback- often using technology to activate a light or bell or more complex environment to illustrate when a particular muscle is contracting.

Hydrotherapy: physical therapy in a warm supportive aquatic environment (where the effects of gravity and often symptoms of pain and stiffness are reduced).

*"the biofeedback machine is good though because you can see it" GP*

*"being able to send the message out out of the water that is how I was able to isolate it"*

*PA*

*"I noticed I could do something and I had to really concentrate. but out of the water." SB*

*"and you could then feel bicep but having that bio feedback was just massive" JT*

There is a thread of 'stiffness limiting function'. Where the effects of prolonged denervation paralysis are felt with the muscle

*"you get stiff and then you can't do things and then the muscles get weaker" GP*

*"it tightens up and it is difficult to manage that" JT*

'Weakness', whilst being expected at first as the muscle returns to function is in one respondent identified, although not seen as an impediment to function.

*"it is weak but I can do it" TB*

#### 9.16.3 Integration of movement & co-contraction

To the process of re-learning to control the muscle function:

*"You can do what you want to do but you are doing it in a different way"*

*"So I have a clip of biceps it doesn't feel when I do that and it flexes when I do that" TB*

*"you are almost having to undo that habit to make the bicep kick in again and it is having that space and time to think more often" JT*

*"am I using my bicep here or is everything else working" JT*

*"I had to really yank my wrist up to get there" LJ*

The common feeling after all of this is that there is still a work of conscious effort. That it is 'not easily integrated'.

*"by constantly keep working that muscle that you have got to connect your brain to that muscle, takes a while but yeah that's what I keep doing and then it takes over" LJ*

The issue of co-contraction is described by many:

‘Co-contraction’: a process whereby muscles that would normally be contracted at differing times to attain opposite effects, (bending /straightening a joint) are fired simultaneously thus reducing or stiffening movement of joints.

*“I over compensate with other muscles” TB*

*“I had to absolutely concentrate on what I was doing try and switch off all the other muscles to try to get it to work because everything was firing instead for it” JT*

#### 9.16.4 Significant fatigue

There is a strong thread of fatigue expressed by all of the patient participants.

*“yeah a lot of fatigue” LJ*

*“the struggle I had was fatigue full stop” GP*

*“20/30 minutes and I’m achy” TB*

### 9.17 Discussion

Our study is a specific, focussed assessment of patient experience in recovery of an essential, motor function- that of elbow flexion (Mennen U. In: The growing hand. Gupta, Kay, Scheker 2000.) following nerve transfer. As such it provides a more specific insight than other objectively focussed papers but is important to consider in reference to the wider picture described in other publications.

Phenomenological research usually involves semi-structured interviews with individuals to gain information about the phenomenon experienced. Smith and Osborn (2003) describe semi-



structured interviews as the exemplary method for Interpretive phenomenological analysis (IPA) and the vast majority of work published using IPA follows suit. The advantages of these include the collection of in depth information about the lived experience of each individual. The limitations are that the individual may only focus on one aspect, rather than giving broad information; which may not be generalised to others. On the other hand, this is the advantage of a focus group discussion; which may give rise to answers, opinions and similarities that the participants may have thought but may not have considered as an answer to the given question. Dunne and Quayle (2016) argue that this data collection technique is ideally suited to research investigating issues of concern to “an accessible, circumscribed and homogenous population”. Dunne and Quayle (2016) further state that they consider that their participants gave essentially the same accounts as they would have done if interviewed individually. In this same publication (Dunne & Quayle 2016) they reflect on the possible impact of group dynamics in focus groups: They consider that through drawing the participants from a population of homogeneous pathology, with intimate knowledge of and concern with the research topic and a judicious use of moderation in the discussion; the potential problem of group dynamics taking precedence over discussion topic can be negated. Flowers (Flowers et al. 2000; Flowers et al. 2001; Flowers et al. 2003) presented structured individual interview data from many differing group discussions and consider that there are synergistic effects produced in group discussion adding to the analysis (Flowers et al. 2001). These concepts were recognised by the author; One of the recognised disadvantages of focus group discussions lies within the concept that some individuals are happier to talk in a group scenario than others. This may lead to a disproportionate trend towards an individual’s experience and poorly reflect others. These considerations were discussed by the author within the research team and eventually a focus group was agreed upon. It was believed that this method would demonstrate both the lived experience and shared experiences between the individuals. In essence this study wished to put equal credence on the individual’s experience and the generalisable signs and symptoms of the

process of motor recovery. The research team adhered throughout to the principle of Alexander and Clare (2004) considering the data collection.

Even though the focus of the discussion was on motor recovery; pain became a very obvious post hoc thematic focus. We have not looked further into the nature of the pain in these patient-participants - their testimony stands alone in this study: it may be that if the stated focus of the group discussion had been pain we would have seen differing themes discussed and explored in differing ways. We do acknowledge that, through their traumatic experience, they have numerous reasons to have both nociceptive and neuropathic pain generators as well as psychological and social magnifiers of pain. Many of the pain themes are related to muscle movement and many link with the theme of muscle fatigue as well. There is a wide experience of pain common to all which; this is an important feature in the experience of recovery of motor function. Pain may predate the reconstruction, be caused by the reconstruction, or be due to reinnervation. It is clear symptoms change and can often improve with time. Pain interferes with the ability to recognise or control movement. It affects motivation and concentration and can directly inhibit movement. It is thus a direct effector of the impact of rehabilitation. It is the related experience that education and preparedness/ expectation management will assist in coping with these symptoms. Thus it is important to relate all these aspects to patients through education not just prior to but also during treatment

In regards to the specific motor experiences of this cohort it is clear that a theme of *function*, above all else, defines the experiences most succinctly. The approach of the common clinical method of force qualification (the MRC muscle grade) is alluded to in the fact that patient-participants relate having no function, notice gaining a flicker (being a moment of very obvious significance for a number of the patient-participants) then contraction with gravity eliminated (in hydrotherapy for many) then gaining the movement out of the pool and then lifting weight. It is though much more nuanced than that. All but one of the patient-participants related a personal

experience of complexity of motor control. The specific challenge in a nerve transfer is to re-learn the motor function - this is an area which has attracted no published literature as far as we can see. The comments of it 'not being a bicep' and the fact that it is functioning but not normally may speak to the control or the proprioception of the muscle. That it is a function that is first activated through attempting the donor function (wrist flexion often) and then is separated as a consciously different function. It appears (from this small cohort's opinion) that it never feels natural.

There is a clear story of fatigue from within all four primary themes with achy pain being described as occurring with effort in 'the complete understanding of pain'. General and specific muscle fatigue are also clear drivers of concern in 'patience and positive thought'. Two forms of fatigue are demonstrated; Firstly, in tasks requiring sustained contraction or repetitive function, are described in 'functionality and daily lifestyle' as being challenging. Secondly in the 'don't call me a biceps' theme it is obvious that even when muscle function is controlled and trained, it still demonstrates significant and function limiting fatigue.

## **9.18 Conclusions**

The patient experience of the return of denervated muscle function is complex. It can only be described by including descriptions all four dimensions of space and time and psychological impact, pain, rehabilitation and function. We have included these aspects into four realms of

- The complete understanding of pain (para 9.13)
- Patience & positive thought (para 9.14)
- Functionality and daily lifestyle (para 9.15)
- Don't call me a Biceps (para 9.16)

In classic clinical assessments of renerated motor function the focus is exclusively on the efferent function (contractile force) to the almost complete exclusion of the afferent function of muscle or wider aspects of patient function or psychology. Reports of MRC grade or dynamometer continuous force measurement are universal and comments about co-contraction and fatigue infrequent. Measurement or even acknowledgment of proprioception, grade-ability of control, integration of movements, praxic control or deep muscle pain are non-existent.

The central role of historic measures (MRC graded peak volitional contraction) to benchmark outcomes is recognised, however, this study of lived experience throws this physician centric focus of efferent function into stark relief. This knowledge will, certainly influence the author's future work, redirecting efforts towards developing tools to provide a more patient directed approach to assessing afferent function. The assessment of; impact on the patient, patient related outcomes, and assessment of function or body image are set to gain traction within a wide area of research in the care of these injuries.

## 10.

# **An Assessment of fatigue and co-contraction, following nerve transfer in re-innervated elbow flexor muscles.**

Beyond peak force assessment: an analysis of re-innervated muscle function through repeated and sustained isometric contractile effort.

*“Muscles are often recorded as normal on the basis of limited clinical tests. These, though exacting, may not take into consideration...the capacity for the muscle to sustain prolonged effort”*

*[Sunderland S 1972]*

### **10.1 Abstract**

#### **10.1.1 Background**

Peripheral nerve injuries are a common outcome after blunt or penetrating trauma. Despite the best efforts of reconstructive surgery muscle re-innervation is often incomplete, resulting in permanent functional disabilities (Shreuders et al 2004, Grinsell and Keating 2014). Peak force is the most commonly used method (chapter five) for assessment but it is only a partial examination of muscle function (chapter three). Fatigue and the effect of co-contraction are important factors affecting the lived experience of motor recovery following nerve injury (chapters eight and nine).

An important step in improving treatment for these patients is to understand the ways in which denervated muscle differs from uninjured muscle. Little is known on the fatigue and co-contraction characteristics of re-innervated muscle following nerve transfer.

#### **10.1.2 Aims:**

The aim of this study is the characterisation of a range of values for the surface electromyographic (sEMG) study of re-innervated human muscle. Furthermore, to study activation frequencies (to assess for fatigue) and co-activation in normal, uninjured muscle and examine the differences to re-innervated muscles. Thus to facilitate a more complete assessment of re-innervated muscle function and potentially identify pathologies amenable to modification to improve the subjective experience of re-innervation.

#### **10.1.3 Methods:**

A cohort of twelve patients, who have recovered force of elbow flexion following unilateral Oberlin nerve transfers, were studied. Data from hand held dynamometry to assess force output, sEMG data to assess force spectra and for quantification of co-contraction, and subjective expression of fatigue during repeated and sustained fatigue experiments were collated. These findings were compared with normal controls.

#### **10.1.4 Results:**

The average peak force of elbow flexion following Oberlin nerve transfer was 7.68Kg ( $\pm 3.8$ ), 37% of the uninjured contralateral side (20.7Kg SD 6.8  $p < 0.0001$ ).

The re-innervated mean biceps mean frequency of 49.66Hz ( $\pm 15.86$ ): 15% lower than uninjured muscle ( $p=0.10$ ). In the injured arm Triceps median frequency was 48.72 Hz ( $\pm 21.23$ ). 19% lower than uninjured muscle. ( $p=0.17$ ). Co-contraction was seen in both arms: in the re-innervated arm at 18.77% in comparison to contralateral limb 12.32% ( $p=0.63$ ).

Re-innervated elbow flexor (Biceps-Brachialis) muscles demonstrate sEMG evidence of fatigue with a fall of mean frequency from 61- 49KHz, a change with a two tailed significance of  $p=0.001$ . with sustained (sixty second) isometric contraction at greater than eighty percent maximal force. No such change was seen in the control group. There was a trend towards an increased co-contraction of re-innervated elbow flexors muscles (biceps brachialis co-contracting with Triceps) when compared with uninjured controls which returns to normal levels as fatigue occurs.

#### **10.1.5 Discussion**

It has been demonstrated in this study of re-innervated human muscle that clinically relevant (chapter nine) characteristics (relating to function and patient experience) are demonstrable through sEMG assessment of median frequency change. Furthermore, these have been demonstrated to differ from the findings in uninjured muscle.

This study shows that re-innervated human muscle has a reduced tolerance to fatigue when under sustained isometric contraction in comparison to controls. This clinical picture reflects experimental work showing an increase in animal models of fatigability in re-innervated muscle (Tonge 1974) and anecdotal patient experience findings (chapter nine).

A trend towards greater co-contraction in the re-innervated limbs is seen, and this reduces as signs of fatigue appear with sustained contraction. This may represent a response to a decreased afferent supply from the muscle and an adaptive attempt to use the antagonist to

provide this feedback. Adoption of these metrics into clinical practice and outcomes assessment will allow a more meaningful comparison to be made between differing treatment options and drive advancements in motor recovery therapy. A similar finding of a decrease in co-contraction as agonist force is lost was found by Hautier et al (2000) in cyclists, (with uninjured muscles) undertaking repeated sprints on an ergometer.

## **10.2 Introduction**

Peripheral nerve injuries are a common outcome after blunt or penetrating trauma. Despite the best efforts of reconstructive surgery muscle reinnervation is often incomplete resulting in permanent functional disabilities (Höke 2006, Gordon et al. 2011, Simon 2015).

The restoration of elbow flexion is a common challenge following nerve injury (to the upper trunk, lateral cord or musculocutaneous nerve) and one where a nerve transfer has become commonly deployed (Oberlin et al. 1994, Leechavengvongs et al. 2006, Ray et al. 2011).

The consequences of skeletal muscle denervation are paralysis and atonia. Furthermore, the muscle is unable to provide afferent proprioceptive feedback to control and coordinate motor functions. This can manifest in impairments such as weakness, pain, stiffness, deficient proprioception, fatigability and co-contraction. All of which may contribute in a reduced ability to perform motor tasks at the pre-injury level.

Even though maximal voluntary force is currently (chapter five) the assessment of choice for muscle assessment, it has been shown (chapter eight and nine) that patients do not recognise this measure as valid in their experience.



Analysis of patient group discussion has shown that fatigue and co-contraction are key experiential outcomes for those affected (chapter nine). This study assessed these patient identified outcomes in re-innervated muscle.

### **10.3 Fatigue**

The symptom of fatigability is a common experience of re-innervated muscle function and one that is ignored when outcomes are based on assessing peak force. Fatigue is commonly defined as an exercise-induced decline in performance (Allen et al. 2008). It is task dependent and produces impairments; either in the activation signal or muscle contractility (Merletti et al. 1988, Matkowski et al. 2011, Molinari et al. 2006). The inability to maintain force over time can mean the inability to perform repetitive tasks, or the inability to maintain a prolonged contraction. All of which provide significant impairment to performing functional tasks.

Fatigability (as assessed through measuring force) can be identified in a number of differing ways: 1) force decrease over time during a sustained isometric muscular contraction; 2) number of isotonic muscular contractions possible (with a constant submaximal effort); and 3) evaluation of the decrease of the muscle force during repetitive isokinetic contractions. (Enoka & Duchateau 2008). Fatigue can also be assessed with measurement of electromyographic parameters: Median frequency fall is a widely used subjective manner to assess fatigue (Merletti 1992). These EMG changes occur prior to any decline in the muscle's mechanical output. They are a measure of the changing metabolic status of the muscle and hence its inability to functionally produce maximal force.

## 10.4 Co-contraction

When assessing functional force output (the muscle's response to work done) and its relationship with fatigue it is important to appreciate and assess all the outcomes of muscular work; not just the resultant force. The concept of co-contraction is an important factor contributing to motor function, and dysfunction. Co-contraction is a process whereby muscular work is negated by action of another muscle (Farmer et al. 1998). It represents deployment of muscular effort against the intention of the movement, it decreases peak force and will exacerbate fatigue for any given contractile effort.

Co-contraction is not just pathologic, it increases control and stiffness of any movement this can be of use in many physiologic conditions. *Pathologic* co-contraction increases work for any given agonist force and thus leads to increased fatigue for any given work (force x time). Co-contraction is measured as a ratio of the antagonist muscles' activity (as measured with Myography) in comparison to the agonist.

The action of active elbow flexion has been selected here for study as it presents a simple uniplanar movement, where the function of the flexor and extensor masses (agonist and antagonist) are easily examinable. This is not the case in all joints, where the force vectors can be much more complicated to resolve.

The intention is to study elbow flexor muscles re-innervated through nerve transfer assessing the impact of co-contraction on force and fatigue.

## 10.5 Aims, objectives and methodology

### 10.5.1 Study questions

1. Is there a relationship is between pathologic co-contraction and fatigue in re-innervated muscle?
2. How best to characterise fatigue in re-innervated muscle and what mechanism may bring this about more or less frequently in a re-innervated muscle?
3. What is the range of normal for these quantities of peak force co-contraction and fatigue relate across normal controls and in re-innervated muscle?

### 10.5.2 Hypotheses

Null Hypothesis (H0): Re-innervated muscle will not differ from normal muscle in its fatigue response to sustained or repeated assessment of isometric contraction.

Primary Hypothesis (H1): Re-innervated muscle will differ from normal muscle in its fatigue response to either sustained or repeated assessment of isometric contraction or both.

### 10.5.3 Aims

1. Characterise normal muscle sEMG behaviour and degree of Co-contraction
2. Characterise nerve transfer re-innervated muscle sEMG behaviour and degree of Co-contraction.
3. Compare the responses of each to repetitive and sustained effort.

#### 10.5.4 Objectives

1. To determine a range of normal values for repetitive and sustained isometric elbow flexor contraction as regards surface EMG spectra, and assessment of co-contraction.
2. Identify differences in re-innervated muscle from these.
3. Identify the relationship between force, fatigue and co-contraction in re-innervated muscle.

#### 10.5.5 Methods

1. Identify or design a sustained and repetitive fatigue protocol for elbow flexion.
2. Identify a cohort of Oberlin transfer patients with documented MRC grade 4 recovery of elbow flexion at greater than 2 years post op.
3. Utilise this population to study fatigue with repeated and sustained contractions models.
4. Examine fatigue via monitoring maintenance of force, subjective reporting of fatigue and mean frequency of the elbow flexors and extensors surface EMG (sEMG).
5. Capture sEMG assessment of co-contraction ratio (antagonist area under the EMG curve / agonist area under the EMG curve).

## **10.6 Materials and Methods:**

### **10.6.1 Patient group**

The Royal National Orthopaedic Hospital Peripheral Nerve Injury database was examined to identify patients who were at a point greater than twenty-four months following Oberlin nerve transfer. This time period (of twenty-four months post surgery) was chosen by consensus agreement between the researchers as a suitable period for full motor recovery to have occurred. Clinically, after this time, there is very little evidence of further reinnervation. These individuals were then further reviewed against the inclusion and exclusion criteria which included documented recovery of a minimum of MRC grade IV within their medical records (full criteria are outlined in Figure 10.5). All patients underwent a standard regimen of post operative rehabilitation. An initial immobilisation period of 6 weeks followed by a milestone driven process of passive mobilisation, active movement and strengthening when signs of reinnervation returned. Sixty-two patients were identified as being eligible to participate in the study. All participants were contacted by post with a letter to invite them to attend a clinical review. If no response was received after one month a second invitation letter was sent. After a process of informed consent a total of twelve participants were subsequently recruited to the study.

### **10.6.2 Control group A**

The contralateral (un-injured) arm of the subject was assessed. This cohort was examined by two independent observers to confirm intra- and inter-rater reliability.

### **10.6.3 Control group B**

A control group of eight volunteers was recruited as a convenience sample from the Royal National Orthopaedic Hospital staff for comparison. Consent was gained and participants included

only if they were aged 27 to 69 years (age parameters of patient group), pain free with no history of significant trauma or surgery to their upper limbs. Inclusion and exclusion criteria were otherwise the same as for the study group (Figure 10.6). Both dominant and non-dominant limbs were assessed in this control group.

NB- The control group A (contralateral limb) was examined for repetitive fatigue. Due to time constraints and many of the study population not being able to continue with prolonged testing a healthy control population was utilised for the control fatigue testing. This further allowed a dominant non dominant comparison to be drawn.

Ethical approval was gained from the NHS ethical board after IRAS application.

**REC reference:** 17/WM/0438

**IRAS project ID:** 231428

After gaining informed consent both groups were invited for examination.

## **10.7 Peak force Assessment: Hand Held Dynamometry**

The protocol for measurement of elbow flexion strength followed the same as published in Quick et al. (2016) (chapter six). The technique aims to bias elbow flexion to biceps and brachialis through positioning in neutral supination with the elbow statically held at 90 degrees.

A M550 MyoMeter (Biometrics, Newport, UK) was used for objective assessments of force. All assessments were performed as 'make tests'; The 'make test' is characterised by the examiner holding the dynamometer stationary while the subject exerts a maximal force against the dynamometer and examiner. An alternative method the 'break' test involves the examiner trying to

overcome the attempt at isometric stability of the subject. The 'make' and 'break' methods of HHD use have been shown to be equally reliable. Bohannon (1988) stated "because the reliability of one procedure was not clearly superior to the other in this study, other factors must determine whether clinicians use make tests or break tests with hand-held dynamometers." We selected the 'make test' over the 'break test' as we consider as others have described directly (Bohannon 1988, Stratford & Balsor 1994) this testing method represents a more valid test of day to day functional ability. The HHD plate was applied to the uppermost distal arm, on the distal shaft of the radius just proximal to the radial styloid with the arm in mid sup-pronation. Force as transduced from the HHD was continuously assessed and recorded by the DATALite software (Biometrics Ltd). The raw data traces were analysed using the same software to record peak force for each of the repeated contractions, area under the force curve (AOCf) (Figure 10.1 and 10.2).

## **10.8 Surface Electromyography (sEMG)**

Surface electromyography (sEMG) data were recorded from the anterior (flexor) and posterior (extensor) compartment of the upper arm using a Biometrics SX230 (Biometrics Ltd Newport, UK) precision bipolar sensory with intra-electrode distance of 20mm. Prior to electrode placement, the skin was cleaned with alcohol. The placement zone was standardised as per Hermens (2000) as 1/3 along a line from the acromion to the centre of the ante-cubital fossa in line with the long axis of the arm. The posterior sEMG is placed mid-way along a line from the posterior acromion to the olecranon (illustrated in Figure 10.31 Page 236).

To assure correct placement of electrodes on the muscle and to protect from any change in position if the adhesive on the electrode failed between sessions, the position of the electrodes was marked on the skin. sEMG signals were recorded using a 4 channel surface EMG Microprocessor controlled programmable gain amplifiers (Data Log MWX8 Biometrics Ltd Newport, UK)

(3-dB bandwidth, 10– 500 HZ) and sampled at a rate of 2048 samples per second per channel.

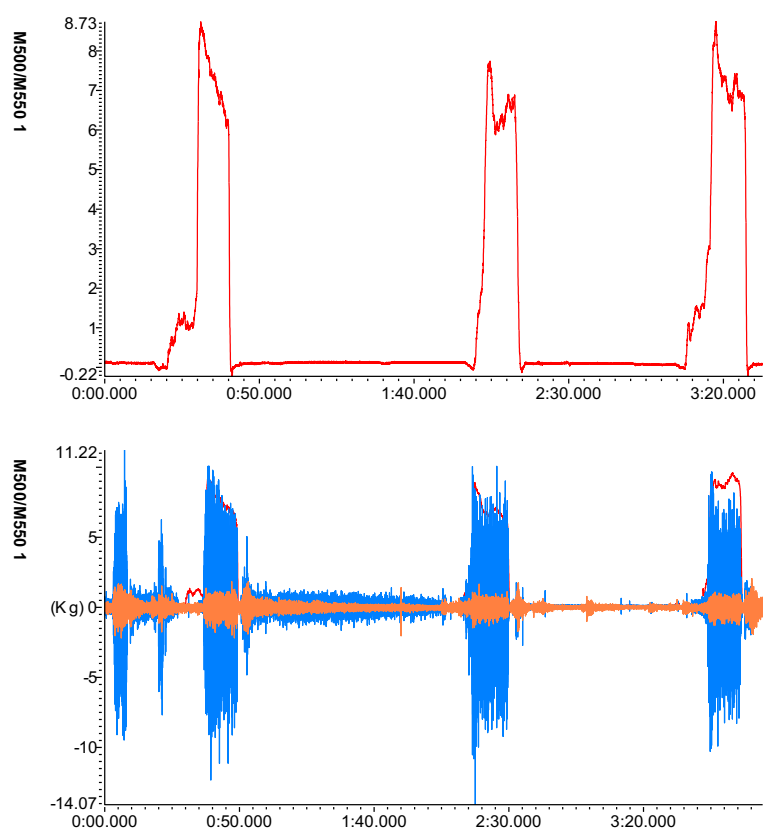
A reference electrode was placed around the contralateral wrist.

The raw EMG was collected and analysed with biometrics software to calculate, Root mean squared EMG (RMS) and area under the RMS curve (AOC sEMG). The Power spectrum was recorded and also rectified by being subjected to RMS then analysed for median frequency data. This EMG data was acquired for both elbow flexor and extensor compartments. The data was further used to calculate a co-contraction ratio. The 60 second sustained maximal contraction was divided into 6 x 10 second blocks and average within those blocks to assess change over time from one block to the others.

## **10.9 Sample Data sheets**

The DATAlite software (Biometrics, Newport, UK) allowed the following assessment, manipulation and calculation from the raw data. As discussed in 10.7 and 10.8 the data was assessed first for the repeated contraction as detailed in 10.7. The first contraction was taken as the individual contraction assessment data for 10.11-10.18. Then the run of three sequential maximal effort contractions were assessed together and shown in 10.19-10.21.

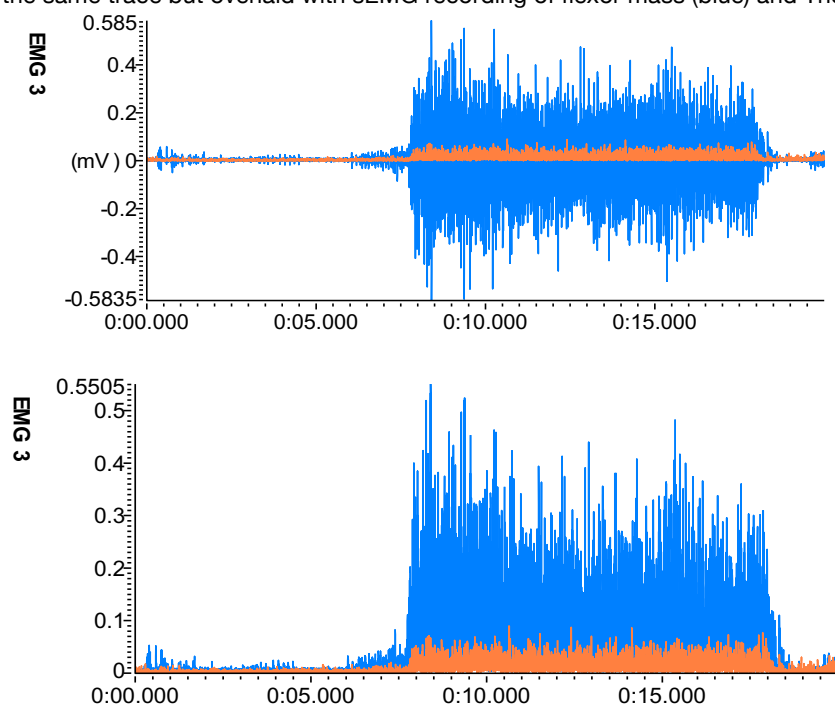


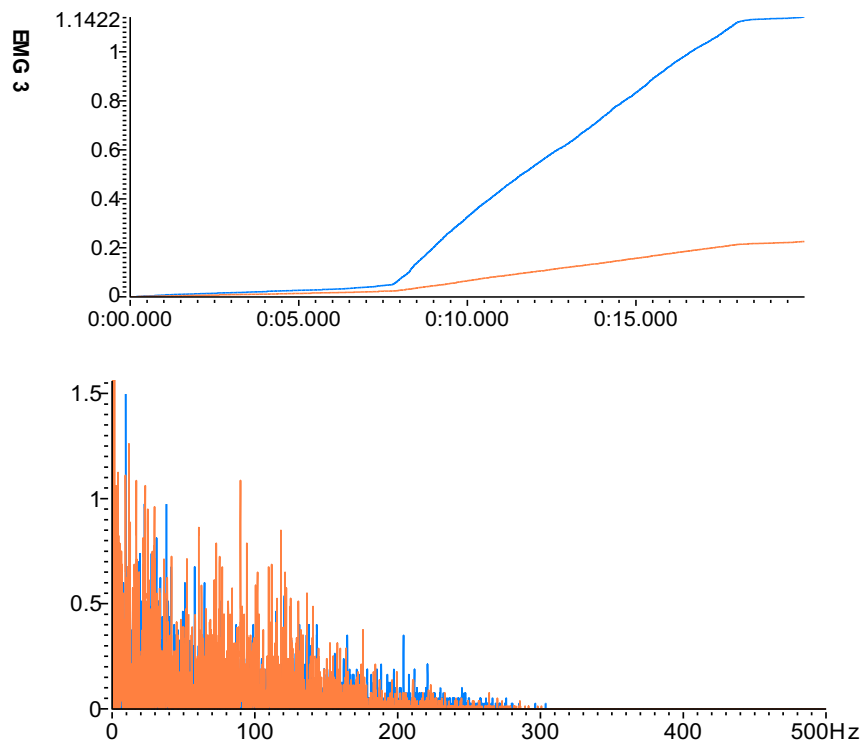


**Figure 10.1:**  
Raw data

Top: Examples of the dynamometer (HHD) recording of three consecutive maximal contractile efforts (KgF on the Y-axis, time in second on the X-axis).

Below the same trace but overlaid with sEMG recording of flexor mass (blue) and Triceps (Orange)





**Figure 10.2:**

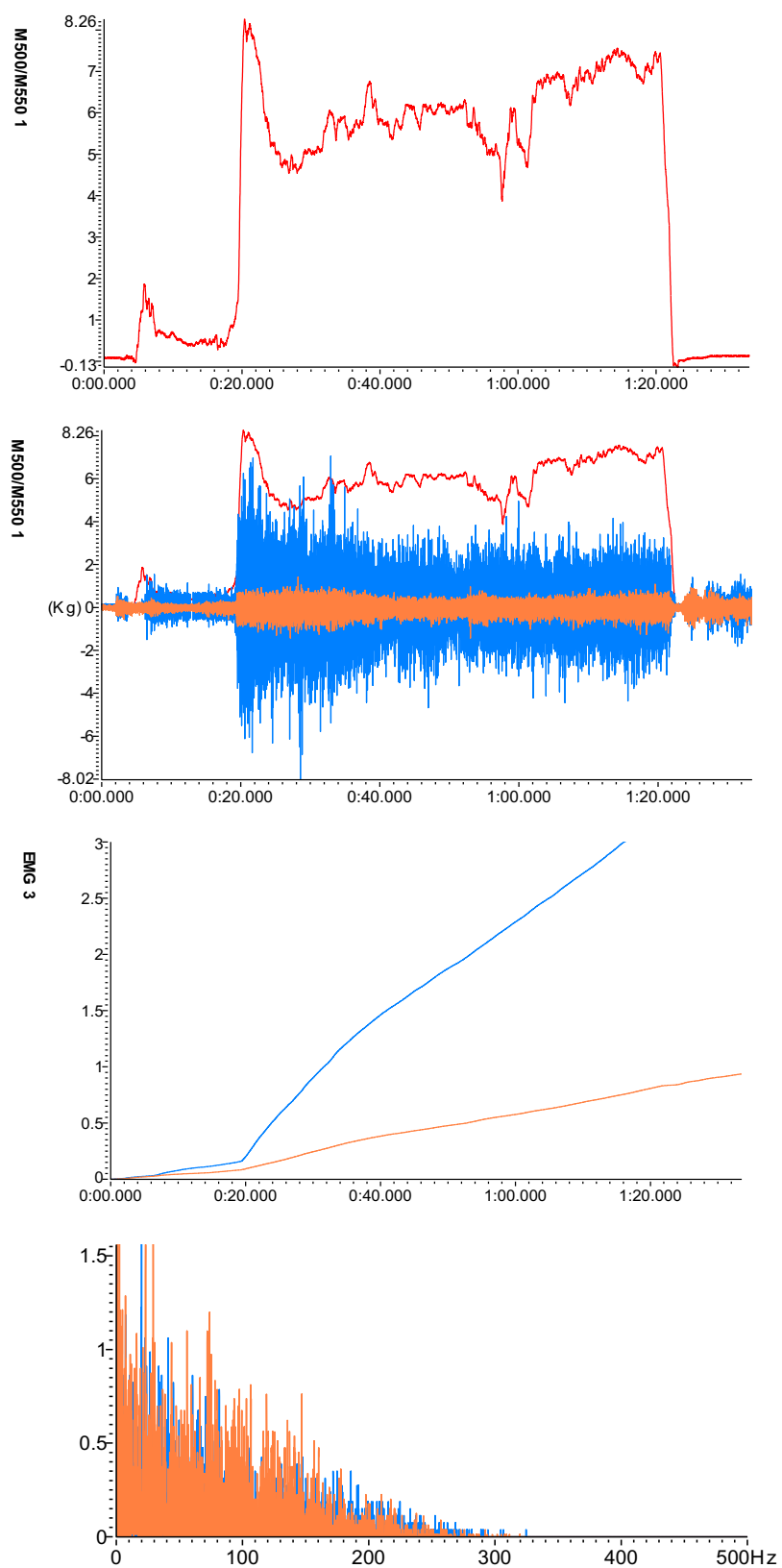
Processing the sEMG data of a single contraction with the DATAlite software:

The top image is the raw sEMG data (blue flexors, orange triceps). Time on the X axis and mV on the Y

Second image Time on the X axis and mV on the Y. RMS (root mean square) processed.

Third image The RMS data is then integrated allowing a calculation of an Area under the curve (AOC) and the co-contraction ratio (orange: antagonist AOC/blue: agonist AOC)

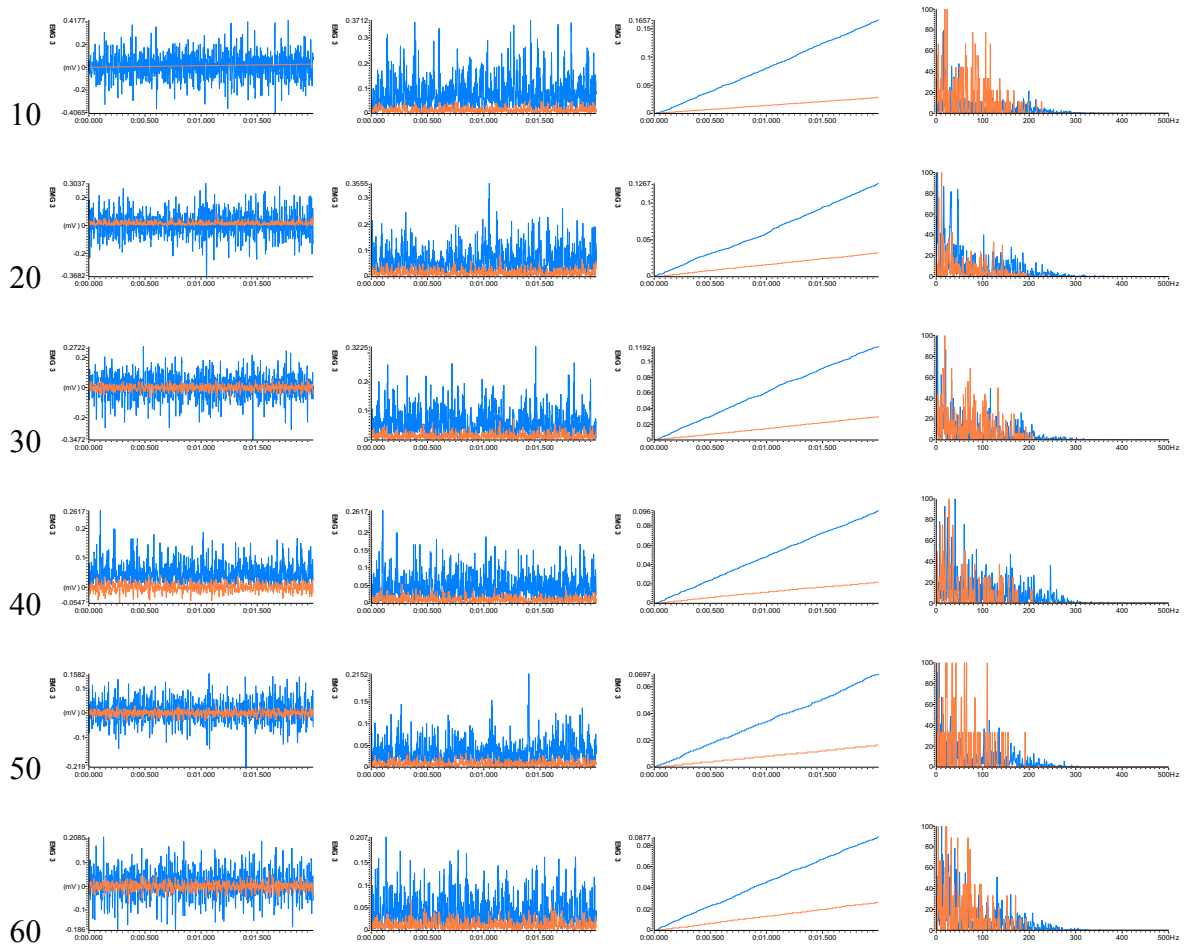
Bottom image: the DATA light software extracts the force spectra from the sEMG trace of the flexors and extensors, (shown here graphically) from which the median frequency was extracted.



**Figure 10.3:** Processing the data for the 60 second contraction in the same manner as for the single maximal contraction for the over all 60 second period (as shown and described in figure 10.2).

In the assessment of the sustained one minute isometric contraction (protocol in figure 10.8) the data was correlated as above for the repeated contractions: first the HHD recording of the minute contraction was assessed for peak force and AOC trimmed to include just the contraction. The sixty second contraction was then divided up within the DATAlite software into ten second blocks and each assessed in isolation. The sEMG data for flexors and extensors, was assessed in the standard manner RMS first then integrated to assess AOC then the final graph is the integrated AOC for the EMG data of flexors and extensors.

A typical block of these six, ten second blocks are shown below (Figure 10.4): Raw data, then RMS, Integrated sEMG, Frequency spectra. This process was undertaken for all the cases. (Figure 10.4 shows just one such individual's 60 second sustained contraction).



**Figure 10.4:**

The graphs here are iterations of the graphs in figure 10.2:

The first column the raw EMG of each 10second period. The second column the normalisation through RMS processing of that data, The Third the work done by each agonist (blue) and antagonist (orange) The sustained contraction data as shown in figure 10.3 was then divided in to six, ten second periods as shown here. Each 10second period was then processed in the same manner as for the single maximal contraction (as shown and described in figure 10.2). Raw data then RMS then integrated then force spectral analysis.

## **10.10 Clinical assessment:**

From patient experience data (presented in chapter nine) we know that fatigue is a significant negative experience of those with re-innervated muscle function. Both repeatability and sustainability have been investigated to provide multifaceted information which better simulates the stresses and demands that are placed on the arm during everyday life. Both affected and unaffected arms were assessed. In order to provide a reference to the patients with nerve injury a convenience cohort of normal subjects were recruited and examined, with the same protocol to gain data for dominant and non dominant arms for comparison.

### **10.10.1 Two measures of fatigue were measured:**

1. REPEATABILITY: Repeated serial peak force contractions as an evaluation of changes in muscle force during repetitive isometric contractions. (3 maximal contractions x 2 with a 60 second break between the two sets)
2. SUSTAINABILITY: Force decrease over time during a sustained isometric muscular contraction (one minute maximal effort contraction).

Due to clinical time constraints we only performed the repeatable contractions in the nerve transferred subjects' normal contralateral limbs. That is to say we were unable to assess the sustainability contraction in the nerve transferred subjects unaffected limbs. All assessments were however performed in the control group in both limbs.

## Subjective fatigue

- To assess subjective fatigue participants were asked to report if they felt the arm fatiguing during the study.

## Objective fatigue

- The sustained force was measured to assess for a reduction in maintained force.
- A validated objective measure of a fall in median sEMG frequency from both the flexor mass and the extensor mass.

Median frequency fall is a widely used subjective manner to assess fatigue (Merletti 1992).

These EMG changes occur prior to any decline in the muscle's mechanical output, they are a measure of the changing metabolic status of the muscle and hence its inability to function produce maximal force.

Inclusion	Exclusion
Unilateral Oberlin/double Oberlin transfer – treated with standard post operative regimen >24 months post surgery Documented activity of elbow flexion of grade 4 MRC or above from clinical notes Adult 18+	Oberlin transfer <24months post surgery Oberlin transfer >24 months post surgery with MRC <4 Oberlin transfer >24 months post surgery proceeded to free functioning muscle transfer Child (0 -18 years) Bilateral Brachial plexus injuries

**Figure 10.5:**  
Table of inclusion/exclusion criteria: patient group

Inclusion	Exclusion
Adult aged 27-69 No history of significant upper limb trauma or surgery (excluding childhood fractures) Pain free	Under age of 27 Over the age of 69 Previous significant upper limb trauma or surgery Pain in upper limb

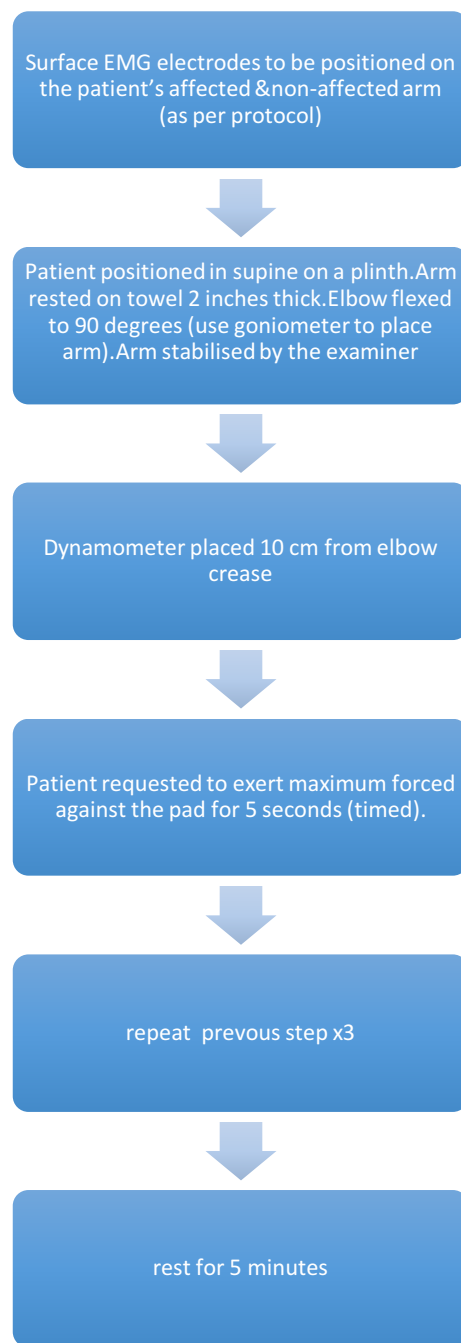
**Figure 10.6:**  
Table of inclusion/exclusion criteria: control group

### 10.10.2 Method for the Muscle Tests:

Repetition of 'make' tests involve the examiner resisting the patient's maximal contraction for 4-5 seconds at mid-range, 90 degrees flexion. A sustained contraction was held in the same position for 60 seconds at 'the strongest you can to keep going for a full minute'.

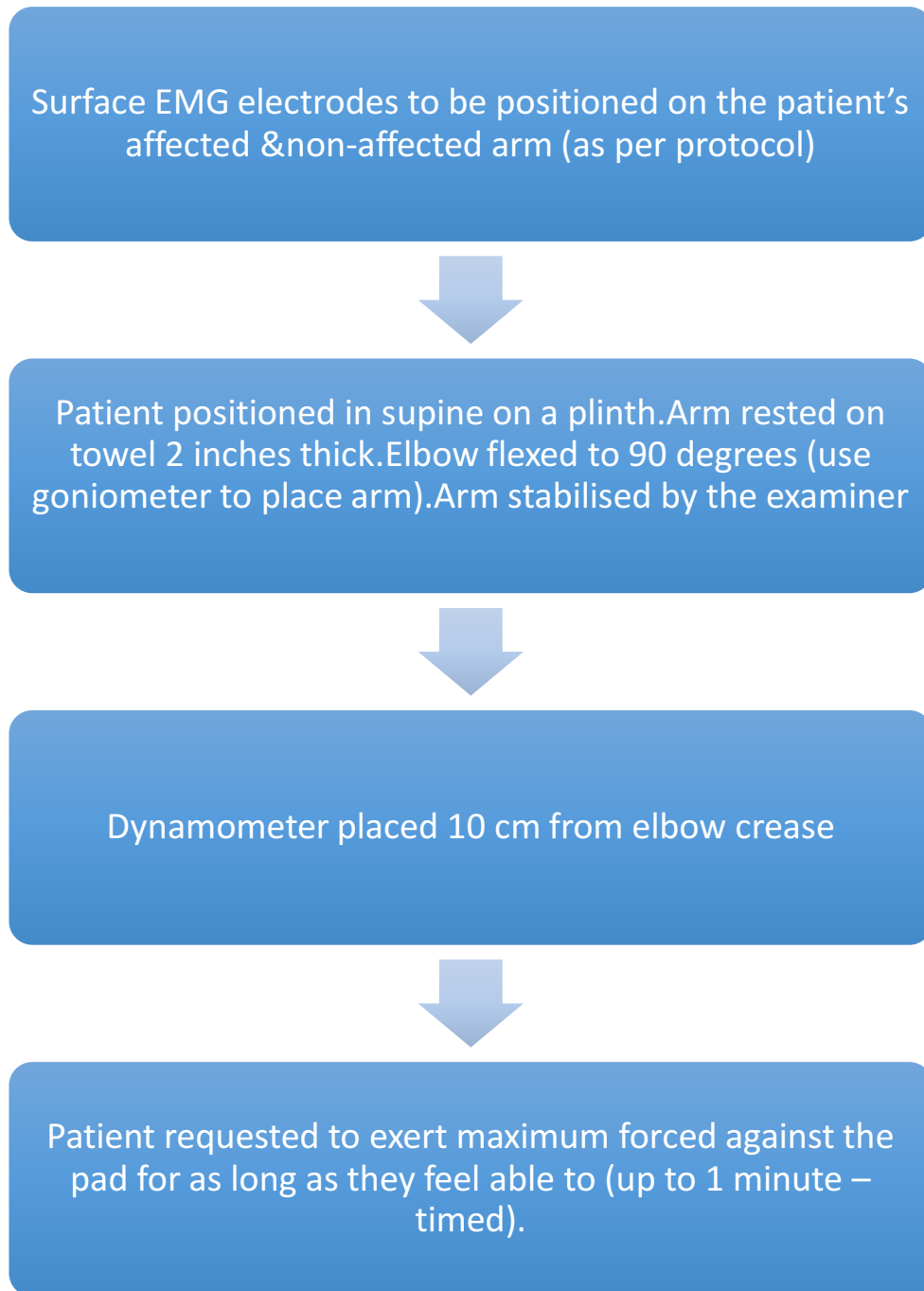
#### 10.10.2.1 Repeatability Test:





**Figure 10.7:**  
Flow chart for the repeatability test for fatigue.

#### 10.10.2.2 Sustainability test:



**Figure 10.8:**  
Flow chart for the sustainability test for fatigue.

### 10.11 Subject demographics

Participant	Gen-der	Age	Affected side	Dominance D-dominant ND-nonDom	Injury	Op date	HHD (Kgf)	
							Affected	Non Af-fected
1 GP	M	47	L	ND	Avulsion C5/6	27/08/14	14.03	19.18
2 LJ	M	27	L	ND	AvulsionC5 RuptureC6	02/10/15	16.27	29.62
3 SM	M	27	L	ND	UT neuroma	23/01/15	8.92	10.01
4 CW	F	69	L	ND	UT neuroma	17/09/10	6.33	15.63
5 MH	M	52	L	ND	UT neuroma	30/09/11	6.83	9.9
6 PA	M	44	L	ND	AvulsionC5 neuromaC6	23/05/14	9.57	25.61
7 SB	M	51	R	D	Avulsion C5/6	15/06/09	12.3	28.97
8 SP	F	47	R	D	E/O Tumour upper trunk	06/07/98	3.12	19.76
9 TH	M	36	R	D	Avulsion C5/6	27/08/10	5.36	19.02
10 TB	M	53	R	D	Muscular cu- taneous nerve humeral #	23/08/96	10.38	28.71
11 MM	M	43	L	D	Avulsion C5/6/7 +/-8	17/10/14	4.65	9.9
12 AW	M	50	L	ND	Avulsion C5/6/7	09/09/09	7.2	30.45

**Figure 10.9:**  
Subject demographics

## 10.12 Control demographics

Study #	Age	Gender	Hand Dominance	HHD (Kgf)	
				Left	Right
1	40	M	R	25.4	31.2
2	28	M	R	24.55	30.03
3	53	F	R	13.92	11.85
4	49	F	R	9.5	13.71
5	61	F	R	14,41	16.88
6	29	M	R	19.12	24.33
7	51	F	R	14.88	15.52
8	36	M	R	24.68	24.15

**Table 10.10:**  
Control Subject demographics

## 10.13 Results

### 10.13.1 Repeatability contractions

During the 6 repetitions it was noticed that:

- The peak force (taken as the peak force attained during any of the 6 consecutive attempts) attained by the re-innervated muscles was 8.67Kg ( $3.12-16.27 \pm 3.8$ ).
- This peak force level was on average 38% of the contralateral side in these individuals.  
Contralateral normal side 22.58Kg ( $9.90-32.53 \pm 7.64$ )
- No subjective signs of fatigue were reported.

In comparing the first and last peak force attempts in the re-innervated muscle over the six receptive contractions there was:

- no significant change in the peak force 7.5-7.9Kg being highly correlated at 0.943 with a significant at a two tailed level for correlation 0.00.
- Biceps median frequency increased from 49.66Hz ( $\pm 16$ ) by 8% to 53.42Hz ( $\pm 17$ ) a non significant change 2 tailed significance (0.52 t -0.67).
- Triceps median frequency rose by 3%; again a non significant change (sig 0.78 t -0.29).
- Co-contraction also did not change 19% to 18% (sig 0.77 t 0.30).
- The repeated contraction data shows that the average variance between the peak force attempts by one individual is 0.798 ( $\pm 0.841$ )

The **peak force** attained across the 6 peak contractions in each group was as follows:

Group	peak force (mean) KgF	SD
Re-innervated n=12	7.68	3.80
contralateral n=12	20.65	6.88
Normal Dominant N=8	20.00	7.16
Normal non Dominant N=8	19.26	6.67

**Figure 10.11:**  
Tabulation of peak force in each group.

The peak force (maximal volitional force) attained (Figure 10.11) in the innervated muscles is 7.68KgF ( $\pm 3.8$ ) which is 37% of the contralateral limb which represents a significant difference ( $p < 0.0001$ ) on a two tailed analysis. (Pair 1 figure 10.12).

There was no seen difference between the normal controls dominant and non dominant arms (Dominant n=8 20KgF  $\pm 7.16$ , and non-dominant n=8 19.26  $\pm 6.67$  -combined n=16 Mean 19.63  $\pm 6.93$ ) where the difference is -0.740 (95% CI -8.16- 6.68)  $p = 0.834$  (not tabulated).

There was no significant difference between the two controls (the contralateral controls and the combined (dominant and non dominant) data from the normal controls (Pair 3 Figure 10.12) difference  $-0.485 \pm 8.77$  95%Ci  $-5.785 - 4.4818$   $p=0.845$ ). Thus the study population have a representative contralateral control, which can be considered representative of an uninjured control.

					95% CI of the difference				
		Mean	Std Devation	Std Error Mean	Lower	Upper	T	Df	Sig (2tailed)
Pair 1	ObRepeat1 Peak- ContraRepeat1 Peak	-12.010	5.786	1.604	-15.507	-8.513	-7.484	12	<0.001*
Pair 2	ObRepeat1 Peak- NormalRepeat 1 Peak	-12.495	8.231	2.283	-17.469	-7.522	-5.474	12	<0.001*
Pair 3	ContraRepeat1 Peak- NormalRepeat 1 Peak	-0.485	8.777	2.434	-5.789	4.818	-0.199	12	0.845

**Figure 10.12:**

Comparison of peak force (KgF) on first contraction  
2 tailed paired samples test to assess difference between the peak force attained by three groups;  
Oberlin (Obrepeat1) contralateral arm group (Contrrepeat1) and the normal group (NormalRepeat1).  
Showing a Significant \*( $p<0.005$ ) difference between the Oberlin group and both control groups in peak force.

When comparing data from the first contraction of each of the group (figure 10.14) it is evident that the contralateral (un-injured) limbs are not different from the normals (controls) and the re-innervated function is significantly less forceful (38% of the force of contralateral side).

The **Median Biceps sEMGs** attained across each group for this first, unfatigued contraction were as follows:

Group	Mean (MedBiceps) Hz	SD
Re-innervated n=12	49.66	15.85
Contralateral n=12	58.11	6.53
Normal N=16	72.02	12.04

**Table 10.13:**

Tabulation of Median Biceps sEMG frequency in each group in the first contraction (unfatigued)  
This shows that in comparison to the normal control's median biceps frequency (mean 72Hz  $\pm$ 12.04) the re-innervated cohort had a lesser mean biceps frequency (49.66Hz  $\pm$ 15.85). in a two tailed test (table 10.11) at  $p=0.005$ . Assessing this as a one tailed test the difference reached a significance for ( $p=0.0002$  95% Ci 11.543-33.178) a lower mean biceps EMG frequency.

Comparing the re-innervated muscles median frequency with the contralateral biceps there is a two tailed difference at the  $p=0.005$  level. The lower mean frequency in the re-innervated muscles may represent a greater proportion of Type II slow twitch muscle fibres as is seen in re-innervated muscles. There was no significant difference ( $p=0.06$  two tailed) when comparing the re-innervated limbs with the contralateral limb.

When assessing correlation (Table 10.14 ) the expected correlation between the contralateral control and the normal control are not seen. The reasons for this are not clear from this data: It is possible, if this a real effect, that the contralateral limb may be under a central and/or systemic effect following the injury to the other limb. More work would be needed to investigate this effect. There was discrepancy between the spread of the figures between the re-innervated ( $\pm 15.85$ ) and the contralateral side ( $\pm 6.53$ ). This shows a greater heterogeneity of groups of motor units in the re-innervated muscles.



Comparing Med Bi-ceps freq groups	Paired correlation (sig)	Mean paired differences (t/sig)
Normal v contra	-.498 (p=.084)	13.91 (3.074/p=.010)
Normal vs re-innervated	-.427 p=(.146)	22.35 (3.407/p=.005*)
Contra vs re-innervated	.353 (p=.237)	8.45(2.049/p=.063)

**Figure 10.14:**

Tabulation of a 2 tailed comparison of the Median Biceps sEMG frequency in each group in the first contraction (unfatigued). There is a significant difference between the normal and the re-innervated group but not the normal and the contralateral group. \* p=<0.005

The **Median Triceps sEMG** across each groups first contraction was as follows

Group	Mean (MedTriceps) Hz	SD
Re-innervated arm n=12	48.73	21.23
Contralateral n=12	60.08	17.85
Normal N=16	65.9077	8.03

**Figure 10.15:**

Tabulation of Median Triceps sEMG frequency in each group in the first contraction (unfatigued)

The re-innervated arm shows no significant differences in comparison to either control (Figure 10.16).

Comparing Med Tric freq groups	Paired correlation (sig)	Mean paired differences (t/sig)
Normal v contra	.379 (p=.202)	-5.83 (-1.27/.0228)
Normal vs re-inner- vated	.112 (p=.717)	17.18 (2.836/p=.015)
Contra vs re-inner- vated	.603 (p=.029)	11.35 (2.316/p=.039)

**Figure 10.16:**

Tabulation of a 2 tailed comparison Median Triceps sEMG frequency in each group in the first contraction (unfatigued). There are no significant differences shown.

Table 10.16 demonstrates no significant differences between the findings in the triceps results at this sample size; but the data shows a similar pattern to the biceps sEMG frequencies; in that there is a larger spread of frequencies in the injured patients (re-innervated *and* contralateral sides) and a trend towards reduced median frequencies in this group and compared to uninjured controls and again further decreased in the re-innervated muscle.

This may imply that the sEMG signals are demonstrating that the re-innervated muscles have a greater heterogeneity of innervation (larger spread of frequencies) and a higher percentage of slow twitch fibres (lower frequencies). Some of these Triceps muscles in the injured limbs will have had an element of nerve injury (this was not controlled for via the inclusion criteria) and this may explain their findings. The fact the contralateral control showed no correlation with the uninjured patients control is of interest and may be explained by a systemic or central process of recovery and rehabilitation of loss of function.

Group	Mean Co-contraction ratio	SD
Re-innervated	0.188	0.144
Contralateral	0.123	0.067
Normal	0.165	0.124

**Figure 10.17:**  
Tabulation of the co-contraction ratios  
(AOC antagonist:Triceps / AOC agonist:Biceps) for each group

The Co-contraction data (Figure 10.17) demonstrates the same trend that we have seen for the data on sEMG for both biceps and triceps. There is a trend toward the un-injured arms being a population intermediate between the injured arm and the normal patient controls. The exception to this, is the force data (Figure 10.10) where the two control populations (contralateral and uninjured patients) were seen to be significantly correlated. These differences may represent a systemic or central adaptation following the injury in the contralateral arm. This study was not designed to identify such an effect.

Comparing co-contraction groups	Paired correlation (sig)	Mean paired differences (t/sig)
Normal v contra	-.196 (p=.521)	.041 (.976/p=.348)
Normal vs re-innervated	-.218 (p=.474)	-.023 (-.398/p=.698)
Contra vs re-innervated	.641 (p=.018)	-.065 (-2.049/p=.063)

**Figure 10.18:**  
Tabulation of a comparison of the co-contraction ratios (AOC antagonist –Triceps/ AOC agonist- Biceps) for each group. Showing that there is no significant difference in these first contraction figures.

There are no significant differences in two tailed tests (Figure 10.18) between any of these variables in the unfatigued contractions. Thus the re-innervated muscles show no differences to the normal controls for co-contraction at this first contraction.

### 10.13.1.2 Repetitions

Three repetitious maximal force attempts were undertaken (as detailed in Figure 10.7). When assessing the first and last contraction within the re-innervated and contralateral groups the changes assessed over multiple repetitions were as shown in Figure 10.19.

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1 (KgF)	ObRepeat 1 peak	7.467	12	3.855	1.069
	ObRepeat 3 peak	7.866	12	3.693	1.024
Pair 2 (KgF)	ContraRepeat 1	19.477	12	6.206	1.990
	ContraRepeat 3	21.120	12	7.173	1.810
Pair 3 (KHz)	ObRepeat BicepMed 1	49.662	12	15.858	4.949
	ObRepeat BicepMed 3	55.105	12	16.402	4.549
Pair 4 (KHz)	ContraRepeat Bicep-Med1	58.108	12	6.529	1.810
	ContraRepeat BicepMed 3	59.646	12	9.235	2.561
Pair 5 (KHz)	ObRepeat TricMed 1	48.723	12	21.231	5.888
	ObRepeat TricMed 3	56.015	12	13.112	3.637
Pair 6 (KHz)	ContraRepeat TricMed 1	60.077	12	17.845	4.950
	ContraRepeat TricMed 3	64.453	12	16.402	4.550
Pair 7	ObRepeat Coco 1	0.188	12	0.144	0.400
	ObRepeat Coco 3	0.177	12	0.104	0.029
Pair 8	ContraRepeat Coco 1	0.123	12	0.067	0.019
	ContraRepeat Coco 3	0.112	12	0.073	0.020

**Figure 10.19:**

Tabulation of the data from multiple contractions

- Pair 1: Oberlin peak force comparing 1st and 3rd contraction
- Pair 2: Contralateral arm peak force comparing 1st and 3rd contraction
- Pair 3: Oberlin median biceps change from 1st to 3rd
- Pair 4: Contralateral arm median biceps change from 1st to 3rd
- Pair 5: Oberlin arm median Triceps change from 1st to 3rd
- Pair 6: Contralateral arm median Triceps change from 1st to 3rd
- Pair 7: Oberlin Co-contraction change from 1st to 3rd
- Pair 8: Contralateral arm Co-contraction change from 1st to 3rd

As displayed in Figure 10.21; there are no significant differences between the first and last contraction force, the median Biceps frequency or median Triceps frequency change, or the co-contraction; in the re-innervated group (Oberlin) or the contralateral controls.

		N	Correlation	Sig
Pair 1	ObRepeat 1 peak & ObRepeat 3 peak	12	0.943	p<0.001*
Pair 2	ContraRepeat 1 & ContraRepeat 3	12	0.860	p<0.001*
Pair 3	ObRepeat BicepMed 1 & ObRepeat BicepMed 3	12	0.262	p=0.384
Pair 4	ContraRepeat BicepMed1 & ContraRepeat BicepMed 3	12	0.802	p<0.001*
Pair 5	ObRepeat TricMed 1 & ObRepeat TricMed 3	12	0.550	p=0.052
Pair 6	ContraRepeat TricMed1 & ContraRepeat TricMed 3	12	0.908	p<0.001*
Pair 7	ObRepeat Coco 1& ObRepeat Coco 3	12	0.523	p=0.067
Pair 8	ContraRepeat Coco 1 & ContraRepeat Coco 3	12	0.223	p=0.464

**Figure 10.20:**

Tabulation of the **correlations** over multiple contractions

- Pair 1: Oberlin peak force comparing 1<sup>st</sup> and 3<sup>rd</sup> contraction – sig correlation
- Pair 2: Contralateral arm peak force comparing 1<sup>st</sup> and 3<sup>rd</sup> contraction– sig correlation
- Pair 3: Oberlin median biceps change from 1<sup>st</sup> to 3<sup>rd</sup> – no sig correlation
- Pair 4: Contralateral arm median biceps change from 1<sup>st</sup> to 3<sup>rd</sup> – sig correlation
- Pair 5: Oberlin arm median Triceps change from 1<sup>st</sup> to 3<sup>rd</sup> – no sig correlation
- Pair 6: Contralateral arm median Triceps change from 1<sup>st</sup> to 3<sup>rd</sup> – no sig correlation
- Pair 7: Oberlin Co-contraction change from 1<sup>st</sup> to 3<sup>rd</sup> – no sig correlation
- Pair 8: Contralateral arm Co-contraction change from 1<sup>st</sup> to 3<sup>rd</sup> – no sig correlation

As shown when assessing the hypothesis that there is a difference between the first and last contraction- correlation is assessed (figure 10.20). There is strong correlation ( $P<0.001$ ) between the first and last re-innervated (Oberlin) contraction of 0.943 and first and last normal control (contralateral) peak force of 0.860. Thus; there is no evidence of fatigue in output; i.e. the first and last contractions demonstrate significant correlation.

The contralateral sEMG assessed median frequency of both biceps and triceps show that there is correlation between the first and last contractions (figure 10.20). There is no such significant correlation seen in the re-innervated arms (figure 10.20).

		N	Difference	Sig
Pair 1	ObRepeat 1 peak & ObRepeat 3 peak	12	-0.399 ±7.22	p=0.798
Pair 2	ContraRepeat 1 & ContraRepeat 3	12	-1.643 ±12/71	p=0.551
Pair 3	ObRepeat BicepMed 1 & ObRepeat BicepMed 3	12	-5.443 ±30.87	p=0.417
Pair 4	ContraRepeat BicepMed1 & ContraRepeat BicepMed 3	12	-1.544 ±3.26	p=0.320
Pair 5	ObRepeat TricMed 1 & ObRepeat TricMed 3	12	-7.292 ±30.83	p=0.164
Pair 6	ContraRepeat TricMed1 & ContraRepeat TricMed 3	12	-4.376 ±32.70	p=0.5366
Pair 7	ObRepeat Coco 1& ObRepeat Coco 3	12	0.011 ±0.230	p=0.8324
Pair 8	ContraRepeat Coco 1 & ContraRepeat Coco 3	12	-0.011 ±0.134	p=0.703

**Figure 10.21:**

Tabulation of the two tailed **differences** in means of multiple contractions

Pair 1: Oberlin peak force comparing 1<sup>st</sup> and 3<sup>rd</sup> contraction- no sig difference

Pair 2: Contralateral arm peak force comparing 1<sup>st</sup> and 3<sup>rd</sup> contraction- - no sig difference

Pair 3: Oberlin median biceps change from 1<sup>st</sup> to 3<sup>rd</sup> - - no sig difference

Pair 4: Contralateral arm median biceps change from 1<sup>st</sup> to 3<sup>rd</sup> - - no sig difference

Pair 5: Oberlin arm median Triceps change from 1<sup>st</sup> to 3<sup>rd</sup> - - no sig difference

Pair 6: Contralateral arm median Triceps change from 1<sup>st</sup> to 3<sup>rd</sup> - - no sig difference

Pair 7: Oberlin Co-contraction change from 1<sup>st</sup> to 3<sup>rd</sup> - - no sig difference

Pair 8: Contralateral arm Co-contraction change from 1<sup>st</sup> to 3<sup>rd</sup> - no sig difference

The table (10.21) above shows that there are no significant differences seen in the repetition contractions between any of the studied parameters. That is to say there is no evidence of any fatigue in this study. This does mean that the protocol for repetitive fatigue has been insufficient to create fatigue in either re-innervated or control populations. There was no change median frequency no change in peak force and no report of subjective fatigue.

#### 10.13.1.3 Summary of repetitive contraction data.

We have established a set of normative data both for single unfatigued contraction in normal and re-innervated muscle:

The contralateral (uninjured) limb cohort develops at peak volitional activity:

a Mean biceps Freq of 58.10Hz ( $\pm 6.53$ )

and triceps of 60.08Hz ( $\pm 17.85$ )

whilst developing 20KgF.

Co-contraction was 12.32%

The re-innervated muscle developed:

a mean biceps mean Freq of 49.66Hz ( $\pm 15.86$ ) : 15% lower than uninjured muscle

a Triceps median frequency 48.72 Hz ( $\pm 21.23$ ). 19% lower than uninjured muscle

at a force of 7.47KgF (40% of the contralateral limb)

Co-contraction was 18.77%

(an insignificance difference which had a 2- tailed significance of 0.63)

There is a decreased median triceps frequency in the involved arms from the first contraction onwards: This is an interesting finding and may relate to an impact from the original traumatic nerve injury to the nerves to triceps, an effect of altering the feedback between biceps and its antagonist or one which may be related to the co-contraction phenomenon. Using this recognised model of repetition fatigue we did not see any evidence of fatigue however.

### **10.13.2 Sustained Fatigue**

Sustainability assessments - 60 second contraction sustained at >80% maximal (Figure 10.22).

To analyse sustained fatigue, we reviewed the mean biceps and triceps frequencies for the first 10 seconds and the subsequent five, ten-second blocks of the one minute sustained contraction (and the mean force over this period). Fatigue was defined as a falling force of contraction over time, subjective report of feelings of fatigue or a sEMG assessed falling median frequency of either biceps or triceps.



Group	Force (Kg) 1-6	Med Bi freq (Hz) 1-6	Med Tri freq (Hz) 1-6	CoCo (ratio) 1-6
<b>Re-innervated</b>	6.28-6.24 ( $\pm$ .2.66-3.17)	61.79-49.44 ( $\pm$ .10.56-14.66)	65.47-55.60 ( $\pm$ .13.55-13.00)	.256-.145 ( $\pm$ .224-.090)
<b>Difference between period 1-6 for re-innervated (significance of change p=)</b>	0.042 (p=.915)	12.353 (p=.001*)	9.869 (p=.055)	0.112 (p=.101)
<b>Normal</b>	17.49-15.13 ( $\pm$ 0.83-5.03)	68.41-65.26 ( $\pm$ .12.87-8.56)	67.31-60.17 ( $\pm$ .8.74-8.90)	.156-.162 ( $\pm$ . 0.79-.101)
<b>Difference between period 1-6 (significance normal change 1-6)</b>	2.36 (p=.011)	3.15 (p=.343)	7.14 (p=.0001*)	-.005 (p=0.684)

**Table 10.22:**

Tabulation of the parameters of force, median biceps and triceps frequency (drop = fatigue) and the ratio of co-contraction between 1(first 10 second block ) and 6 (last 10 second block) of the 60 second sustained contraction. With the SD of each below. The the significance of the change between 1-6 in that parameter. For both re-innervated populous and the normal. \* denoted significant result  $p < 0.05$ .

	Re-innervated function	Mean	N	Std Dev	Std Error Mean
<b>Pair 1</b> (KgF)	ObFatigue1 Peak	6.279	13	2.658	0.737
	ObFatigue6 Peak	6.237	13	3.172	0.880
<b>Pair 2</b> (Hz)	ObFatigue1 BicMed	61.792	13	10.588	2.937
	ObFatigue6 BicMed	49.436	13	7.815	2.167
<b>Pair 3</b> (Hz)	ObFatigue1 TricepMed	65.469	13	13.555	3.760
	ObFatigue6 TricepMed	55.600	13	13.000	3.605
<b>Pair 4</b> (ratio)	ObFatigue1 CoCo	0.256	13	0.224	0.062
	ObFatigue6 CoCo	0.145	13	0.090	0.025

**Table 10.23:**

Tabulation of Paired samples statistic data for the 6 periods of sustained fatigue (each period a 10 second block of the sustained 60 second contraction) in the **Nerve transferred** arm. Compare with Table 10.21 for the normal control data. ObFatigue1 data relates to the first period of the fatigue (0-10 seconds). ObFatigue6 relates to the last period (50-60seconds). Peak is peak force (KgF). BicMed is the Median biceps frequency (Hz) TricepMed is the Triceps median frequency (Hz). CoCo is the Co-contraction ratio (AOC antagonist/ AOC agonist).

	Re-innervated function	N	Correlation	Significance
<b>Pair 1</b> (KgF)	ObFatigue1 Peak & ObFatigue6 Peak	13	0.899	P<0.001*
<b>Pair 2</b> (Hz)	ObFatigue1 BicMed & ObFatigue6 BicMed	13	0.472	0.104
<b>Pair 3</b> (Hz)	ObFatigue1 TriceMed & ObFatigue6 TriceMed	13	0.202	0.507
<b>Pair 4</b> (ratio)	ObFatigue1 CoCo & ObFatigue6 CoCo	13	0.181	0.553

**Table 10.24:**

A correlation table for the changes between the first and last sectors of the fatigue sustained contraction for the **Nerve transferred** arm. Peak force (unchanged over the period) and the sMEG changes in biceps, triceps and the change in co-contraction ratio. \* denotes significant correlation p<0.05. The force is maintained well over the 60 seconds but there are no other correlation.

There is no drop in force over the period 1 to 6 in re-innervated muscle. Force is maintained over the sixty second contraction.

	Normal function	Mean	N	Std Dev	Std Error Mean
<b>Pair 1</b> (KgF)	NormFatigue1 Peak	17.492	16	5.836	1.459
	NormFatigue6 Peak	15.131	16	5.028	1.257
<b>Pair 2</b> (Hz)	NormFatigue1 BicMed	68.413	16	12.875	3.219
	NormFatigue6 BicMed	65.253	16	8.563	2.141
<b>Pair 3</b> (Hz)	NormFatigue1 TricepMed	67.306	16	8.745	2.186
	NormFatigue6 TricepMed	60.169	16	8.902	2.225
<b>Pair 4</b> (ratio)	NormFatigue1 CoCo	0.156	16	0.079	0.020
	NormFatigue6 CoCo	0.162	16	0.101	0.025

**Figure 10.25:**

Tabulation of data for the 6 periods of sustained fatigue (each period a 10 second block of the sustained 60 second contraction) in the **normal controls**, Compare with Table 10.19 for the re-innervated muscle data. . NormFatigue1 data relates to the first period of the fatigue (0-10 seconds). NormFatigue6 relates to the last period (50-60seconds). Peak is peak force (KgF). BicMed is the Median biceps frequency (Hz) TricepMed is the Triceps median frequency (Hz). CoCo is the Co-contraction ratio (AOC antagonist/ AOC agonist).

	Normal function	N	Correlation	Significance
<b>Pair 1</b> (KgF)	NormFatigue 1 Peak & normFatigue 6 Peak	16	0.831	p<0.001*
<b>Pair 2</b> (Hz)	NormFatigue1 BicMed & NormFatigue6 BicMed	16	0.333	p=0.208
<b>Pair 3</b> (Hz)	NormFatigue1 TriceMed & NormFatigue6 TriceMed	16	0.875	p<0.001*
<b>Pair 4</b> (ratio)	NormFatigue1 CoCo & NormFatigue6 CoCo	16	0.868	p<0.001*

**Figure 10.26:**

A correlation table for the changes between the first and last sectors of the fatigue sustained contraction for the **Normal Control** arm. Peak force (unchanged over the period) and the sMEG changes in biceps, triceps and the change in co-contraction ratio. \* denotes significant correlation p<0.05. There is clear maintenance of the force in biceps and no fatigue in triceps or increase in co-contraction.

Similar to the re-innervated muscle there is sustained contraction over the sixty second contraction as shown by a correlation between period 1 and 6.

Re-innervated Muscle					95% CI of the difference				
		Mean	Std Deviation	Std Error Mean	Lower	Upper	t	Df	Sig (2tailed)
Pair 1	ObFatigue1 Peak-ObFatigue6 Peak	0.423 KgF	1.405	0.390	-0.807	0.891	0.109	12	p=0.915
Pair 2	ObFatigue1 Bic-Med-ObFatigue6 Bic-Med	12.354 KHz	9.754	2.710	6.460	18.248	4.567	12	p=0.001*
Pair 3	ObFatigue1 TriMed-ObFatigue6 TriMed	9.869 KHz	16.774	4.652	-0.267	20.006	2.121	12	p=0.055
Pair 4	ObFatigue1 CoCo-ObFatigue6 CoCo	0.111	0.226	0.063	-0.025	0.248	1.777	12	p=0.10

**Table 10.27:**

2 tailed comparison in **re-innverated muscle** sustained fatigue (60 second). The median frequency of the biceps from the first to the last sector in the sustained contraction- showing a significant difference (a drop of 12.35 , range 6.46-18.25) demonstrating fatigue. \* shows significance  $p < 0.05$ . Compare with Table 10.24 where the normal muscle data is shown for the same sustained fatigue.

Fatigue is evident in the re-innervated muscles, as demonstrated by a drop in the median frequency over the period from the first to the last ten-second block in this sustained contraction.

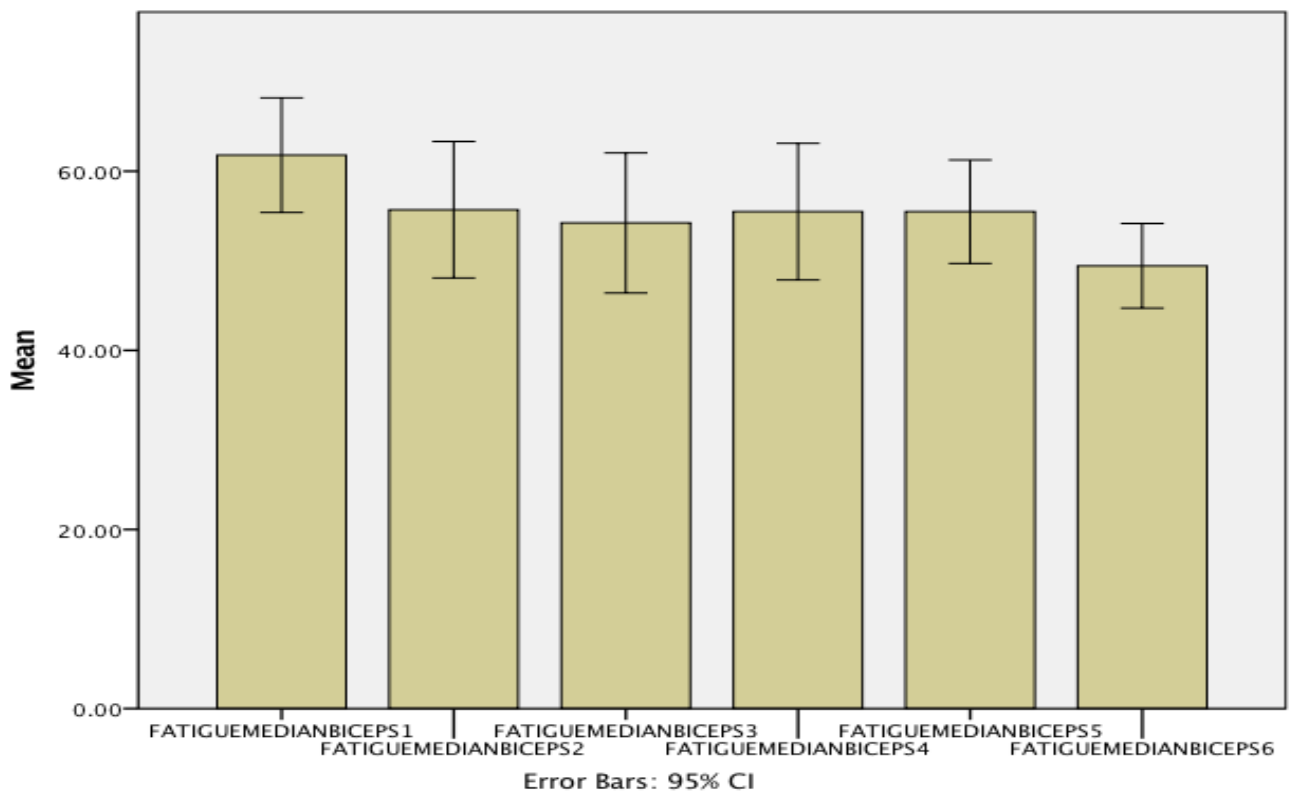
Normal Muscle					95% CI of the difference				
		Mean	Std Deviation	Std Error Mean	Lower	Upper	T	Df	Sig (2tailed)
Pair 1	Norm Fatigue1 Peak- NormFatigue6 Peak	2.361 KgF	3.247	0.812	0.630	4.0917	2.908	15	0.011
Pair 2	NormFatigue1 BicMed- NormFatigue6 BicMed	3.150 KHz	12.873	3.219	-3.710	10.010	0.979	15	0.343
Pair 3	NormFatigue1 TriMed- Norm Fatigue6 TriMed	7.138 KHz	4.418	1.104	4.783	9.492	6.462	15	0.000**
Pair 4	NormFatigue1 CoCo- NormFatigue6 CoCo	0.005	0.051	0.013	-.323	0.022	-.415	15	0.684

**Figure 10.28:**

2 tailed comparison in **normal muscle** in sustained contraction there is no change between the median frequency of the biceps from the first to the last sector in the sustained contraction. The triceps does show a significant change however this change of 7.138KHz is less than the change in fatigue we see in the biceps in the re-innervated muscles of 12.354.

IN the normal arms the Co-contraction ratio is 15% and similar to the end point of the drop in Co-contraction ratio in the re-innervated arms.

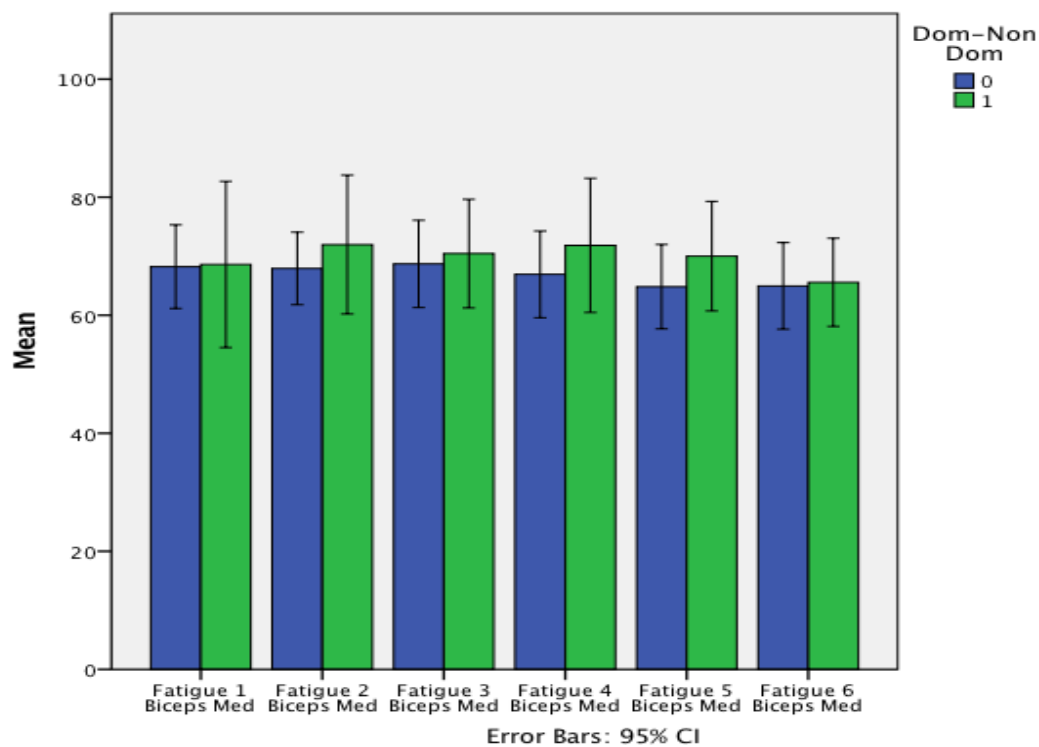
There is no change in the median frequency of the biceps in the normal muscle controls. There is no evidence of fatigue in these muscles.



**Figure 10.29:**

Histogram of re-innervated muscle (Oberlin) showing the drop in median biceps frequency (Y axis) over time as divided by the 6 10 second time periods (X axis). As shown in 10.23 there is a drop of 12.35 from 1- to 6- sector which is significant (0.001).

Comparing the biceps change over time the re-innervated biceps are showing a significant drop in median frequency pattern. When we look at the drop of Biceps median frequency graphically we see this drop occurs in the last 10 second period of the minute sustained contraction:



**Figure 10.30:**

Histogram of the normal controls (both limbs) showing no drop in median biceps frequency (Y axis) over time as divided by the 6 10 second time periods (X axis). No significant change demonstrated.

There is no change in the median frequency of biceps in the normal controls- no evidence of fatigue and no difference between dominant and non dominant arms.

In the above data we see that the force is well maintained in the re-innervated biceps flexion at 6.2 Kgs (6.2/7.68Kg= 80%). Change over 60 seconds from 6.28- 6.24 is not significant ( $p=0.915$ ). Over this period of sustained contraction at 80% peak force the Biceps demonstrate the onset of fatigue (in that the biceps median frequency has dropped over this period from 61-49KHz (44Hz a change with a two tailed significance of (0.001). The Triceps did not fatigue (median frequency drop of 9.87Hz was not significant  $p = 0.055$ ). The Co-contraction ratio in the re-

innervated arms (triceps AOC/Biceps AOC) over the sustained contraction decreased (0.256-0.145) a change that was non significant ( $p=0.09$ ) but the trend was for a decrease in the co-contraction and a tightening of the spread of values and in doing so has dropped to near normal (ratio of 0.144).

In the normal population: the biceps does not show any significant fatigue but the triceps does have a significant reduction in its median frequency of 7.14 Hz demonstrating fatigue. There was no significant change in the co-contraction.

During the 60 second sustained isometric contractions it was noticed that:

- The peak force attained in the re-innervated elbow flexors was 6.90Kg (SD 3.07).
- This sustained force is 80.69% (46.96-108.67) of the peak possible.
- The force did not deviate significantly over the 60 second sustained contraction ( $p$  value of 0.00).
- The mean frequency of sEMG biceps in the re-innervated muscles fell during the last 10 second period in the re-innervated muscle biceps median frequency dropped over the 60 second period from 61- 49KHz (44Hz a change with a two tailed significance of 0.001).
- Co-contraction in the re-innervated arms dropped; the trend was for a decrease in the co-contraction and a tightening of the spread of values and in doing so has dropped to near normal (ratio of 0.144).
- In the controls: the biceps does not show any significant fatigue but the triceps does have a significant reduction in its median frequency of 7.14 Hz demonstrating fatigue. There was no significant change in the co-contraction.
- No subjective signs of fatigue were reported in either group.





**Figure 10.31:**  
Clinical photograph demonstrating the position of surface electrodes as described in 10.8 pg 202.

## 10.14 Conclusions

This study set out to:

1. Identify a cohort of Oberlin transfer patients with documented MRC grade 4 recovery of elbow flexion at greater than 2 years post operatively.
2. Utilise this population to study fatigue with repeated and sustained contractions models.
3. Examine fatigue via monitoring maintenance of force, subjective reporting of fatigue and mean frequency of the elbow flexors and extensors surface EMG (sEMG).
4. Capture sEMG assessment of co-contraction ratio (antagonist area under the EMG curve / agonist area under the EMG curve).

These data have demonstrated that:

- a re-innervated biceps demonstrates a differing spectrum of EMG frequency in comparison to the contralateral limb- and thus by inference a change in spectrum following nerve injury. Via a comparison of the means this difference does not read a significant difference however the populations are very different 49.66 SD 15.86 in reinnervation in comparison to 58.11 SD 6.53 in their opposite limb with  $t=-2.05$  at a two tailed significance of 0.063
- the re-innervated biceps contractions elicit more co-contraction- suggesting either an injury to the triceps (but they have a normal frequency spectrum in comparison to the contralateral side), or, a response to a pathology of the afferent signal from the re-innervated biceps. This difference is small 6% and has a t score of 2.049 with a two tailed significance of 0.067
- with 3 repeated contractions there is no evidence of fatigue: the biceps med frequency is unchanged
- re-innervated biceps under sustained contraction (80% maximal for 60 seconds) fatigues more than an undamaged biceps.

- this fatigue is linked with a drop in the Co-Contraction ratio with the biceps' antagonist- perhaps in a method to protect the fatiguing muscle.

Several studies have attempted to compare the variations in fatigue during prolonged isolated muscle contractions (Place et al. 2009, Neyroud et al. 2012, Vøllestad 1997) and some following nerve pathology in humans (Pagala et al. 1993; Allen & Doherty 2011). Only two publications have been identified which focused on assessing parameters of fatigue following re-innervation of elbow flexion in humans (Chammas et al. 1997, Maricq et al. 2014). Both of these studies recognise the clinical validity of the issue of fatigue, and both use dynamometry to further the understanding in this area. The first (Chammas et al. 1997) set out to compare the variations of muscle isometric strength during a prolonged effort between graft reconstructed, re-innervated muscle, and normal, uninjured human muscles. The enrolled ten subjects (four with unilateral upper trunk injuries and six with unilateral total plexus injuries) were treated with nerve grafts (in nine subjects) and an intercostal nerve transfer (using three intercostal nerves) in one. They were followed up at an average of twelve years (range 7.5-16 years). A supportive device was used (as many subjects did not have shoulder control) which held the arm in an internally rotated position. Injured arms were compared with the contralateral arm. Isometric force was assessed with a dynamometer with the elbow at 90 degrees. Maximal force was recorded from a series of three, five-second maximal efforts. A fatigue phase; where by a 100% maximal effort was requested for one minute. Then a subsequent period where 50% maximal effort was requested for 5 seconds every fifteen seconds during five minutes then at six, seven and ten minutes. Their results showed the peak force was twenty-two percent of the contralateral normal side (with no difference between the upper trunk and the total plexus groups).

The fatigue index (a measure of percentage of maximal force) fell by 10% within twenty seconds. This was similar between the normal and the re-innervated arms.

The second study (Maricq et al. 2014) also recognised the clinical issue of fatigue and the deficiencies of studying motor outcomes with only MRC grading. This paper assessed nerve transfer re-innervated elbow flexion (in five subjects) at a mean follow up of forty-seven months. Their trial end point was a 50% reduction in force. They utilised a isokinetic elbow flexion test (of six repetitions of elbow flexion/ extension at 60 /s speed, then six at 90 /s, then four at 45 /s. Data was then collected during three cycles at 60 /s and five cycles at 120 /s.). Then a sustained isometric test at 45 degrees elbow flexion, the time was measured for a 50% decrease of maximal contraction strength. Their population demonstrated 70% peak force from the re-innervated muscles in comparison to their normal. Maricq found that *'No patient was able to maintain an isometric contraction during sufficient time to evaluate fatigability'* due to muscular pain. Their summary was that *"the recovered elbow flexion remains quite weak, despite at first approximation an acceptable clinical result. There seems to be also an extremely quick muscular fatigability, causing pain upon sustained isometric contraction."*

Historically these studies of fatigue only used assessed change in force output recording but signs of fatigue can also be objectively measured independently of the 'mechanical manifestations' (Cifrek et al. 2009). It is possible to interpret changes in myo-graphic signals to show the impact of biochemical and physiologic changes prior to loss of contractile force (De Luca 1994, Stulen & De Luca 1982).

As a muscle fatigues there is a change in the power spectrum as detected from surface electrodes. Under fatigue there is an increase in the amplitude of the low frequency band and a relative decrease in the higher frequencies. Physiologically, this reduction in frequency has been attributed to changes in conduction velocity, changes in intra-muscular pH, modification in the recruitment and synchronisation of the motor units and the fibre (Wang et al. 2014, Rogers & MacIsaac 2013, Dobkin 2008). The muscle frequency spectrum is a complex spread of electronic signals and derived variables from it have been assessed to quantify the degree of fatigue.

These include central tendency measures (mean, peak and median) and ratios of the power of high and low frequency bands. Since the muscle frequency spectrum from the surface electrodes is not normally distributed the often used median frequency was selected as the marker of fatigue (Yaar & Niles 1992, Thongpanja et al. 2013, Allison & Fujiwara 2002).

Many clinical reports present series of patient demonstrating co-contraction around the elbow (Hierner et al. 2001, Rollnik et al. 2000, Hébert et al. 1989, Rouard & Clarys 1995). The degree and the manner of co-contraction are known to vary with fatigue within a normal population in isometric elbow flexion (Williams et al. 2002). It was not possible to identify any clinical studies in nerve injury which present an assessment of the co-contraction ratio (or any other similar objective continuous measure of co-contraction) or any that link this with fatigue. It has not been known what the incidence of pathologic co-contraction is in re-innervated muscle.

## **10.15 Discussion**

The data has demonstrated novel data for force spectra within re-innervated human muscles and assessed co-contraction ratios. The findings of this study are novel findings in a human clinical model of nerve injury and contribute to the development of understanding about the impact of re-innervation on human muscle function. The two previous studies in this area (Chammas et al. 1997; Maricq et al. 2014) have been advanced upon in that fatigue has been demonstrated within this model and characterised with electromyography.

It has been clear in this study that the patient's experience of motor recovery following nerve injury was not represented by the standard method of peak force assessment. The assessments have over this time evolved from routine use of MRC grade to the use of a HHD to assess force

continually (Quick et al. 2016). When this was compared to patients' expectation and satisfaction following nerve transfer there was little correlation found between patient experience and their peak force of elbow flexion. In order to progress a more comprehensive appreciation of re-innervated muscle function the study was to re-focused on the elements which have been identified as meaningful to the patients; Through a thematically coded focus group discussion exercise fatigue was identified as a central theme of muscle recovery and through deploying a redesigned study, and widening the examination to include co-contraction as an important feature of this experience; thus relevant data were collected. Thus the state of clinical knowledge agreed that fatigue was a clinical issue. It further suggested that there may be a difference between the outcomes as regards fatigue between nerve grafting and nerve transfer, that there may be deep pain associated with fatigue.

This study set out to characterise the pathology of human muscle dysfunction following re-innervation; with specific attention to fatigue and the contribution of co-contraction: However, it cannot be ignored that the success of re-innervation following chronic muscle denervation has many contributory elements: All of these factors may contribute to the clinical dysfunction that is demonstrated in this model:

- The effects of chronic denervation on the distal stump are well characterised (Fu 1995) and are majority contributors to the success or failure of the acutely axonotomised donors in this model (and still in the chronic axotomy when graft repair is performed).
- The changes within the muscle with progressive loss of capillary density, motor fibre number, down regulation in contractile protein, increase in intracellular fibrosis and reduction of satellite cell numbers (Carlson 2014).
- There is also evidence for a higher order pathology which is a factor with neural fatigue interacting with muscular fatigue (Taylor et al. 2016)
- Psychological impact of injury and paralysis to recovery of function (Collins & Long 2003)

The findings of this study are presented as a further characterisation of the clinical problem and do not offer any evidence towards etiology of differential contributions of the above pathologies to this pathology. That will be the aim of future prospective studies.

This study has demonstrated that a cohort of subjects following nerve transfer to elbow flexion have developed a mean peak force of 7.68 Kg SD 3.8 (38% of the contralateral side) this is within a range of what others researchers have found. [see literature review in Chapter 7] thus establishing this to be a representative population to further study.

#### **10.15.1 The selection of sEMG median frequency assessment of fatigue**

There is debate surrounding the use of this myoelectric marker of muscle fatigue; it is used by many experienced authors in this area (Mannion & Dolan 1996; Phinyomark et al. 2012) and has been shown to be reliable and repeatable (Gazzoni et al 2017). There are other more direct markers of muscle metabolic change; as discussed below:

#### **10.15.2 Reduced Mean frequency in unfatigued nerve transfer re-innervated human muscle**

The finding that re-innervated muscles demonstrate spectra that have an un-fatigued power spectrum which is 80% lower than the contralateral controls is likely to be a demonstration of the impact of reinnervation; where by the motor pools are larger less heterogeneous and a greater percentage of slow twitch type I motor units (MUs). The fast twitch/ type II units are of the frequency range = 126 - 250 Hz and due to their aerobic nature fatigue more quickly than the tonic. Slow twitch /type I units which have a spectral range of 20-125Hz. Thus the spectrum shifts

downwards; with the onset of fatigue and the build up an hypoxia metabolic load. Also it is decreased if the new, un-fatigued, population of a re-innervated muscle has a higher ratio of type I fibres. As shown by Bagust and other authors (Bagust et al. 1981, Dum et al. 1985, Gordon et al. 1988) the characteristics and ratios of motor units are determined by the innervating axons. That is to say the type and make of the motor units and thus their fatigue resistance are characterised by the type of axon that establishes contact. Foehring (1986) and Rafuse (1998) demonstrated; even within self-re-innervated (analogous with the spontaneous recovery or nerve graft repair patients) muscles; a growth in the MU pool with a decrease in the MU number and an increase in the ratio of type I MUs.

### **10.15.3 Demonstration of earlier Fatigue in re-innervated human muscle**

The results demonstrate no effect of fatigue with 6 repeated maximal contractions either on subjective or objective assessments. In fact, anecdotally, the subjects reported that they felt stronger throughout the attempts. In that none of the subjects demonstrated fatigue within the repeatability trial it was obviously therefore submaximal in stressing the ability of the muscles (both uninjured and re-innervated). This is a clear weakness of the study design.

The sustained isometric model of fatigue did however demonstrate a differential response between the re-innervated muscles and uninjured controls.

The assessment of a muscle with sEMG demonstrates the population of motor units within the muscle, the Fast twitch (type II) units have a higher frequency of activity and make up the top end of the spectra. Thus it is shown that a muscle that is re-innervated will have a novel force spectra, with a right shifted spectra as there is a higher ratio of type I fibres. These data suggest such a trend. During fatigue significant changes occur in the intra and extracellular environment (Dimitrova & Dimitrova 2003) the increase in intramuscular pressure determines occlusion of blood flow (Matkowski et al. 2011) the electric properties of the muscular fibre membrane change (Dimitrova & Dimitrova 2003), and myoelectric manifestations of muscle fatigue become



evident (Merletti et al. 1988). These myoelectric changes with fatigue are recognised by examining the sEMG frequency domains; median frequency fall is a widely used subjective manner to assess fatigue (Merletti et al. 1992). These EMG changes occur prior to any decline in the muscle's mechanical output, they are a measure of the changing metabolic status of the muscle and hence its inability to function produce maximal force.

#### **10.15.4 Co-contraction ratios in re-innervated human muscle**

This study has shown no difference (2 tailed significance  $p=0.63$ - insignificant at an alpha of 0.05) between the re-innervated and contralateral arms (18% re-innervated vs 12% contralateral). The levels of co-contraction drop over the fatigue period from 25.6 % (SD 22.4%) to 14.5% (SD 9%) a change again not reaching an alpha of 0.05 (0.101).

These findings are in line with the literature;

Frey-Law (Frey-Law 2013) found when assessing co-contraction (in healthy subjects' elbows and knees) that muscle co-contraction is determined by local, joint-specific, and generalised, individual-specific influences. They also found large variation in person to person difference concluding that person-specific variations in the propensity to use co-contraction as a motor-control strategy across multiple joints indicate the presence of a generalised response.

The levels of co-contraction in neuromuscular disease showed similar finding with no differences (but a trend towards a difference with large SDs in both groups). In a study assessing the levels of co-contraction in hamstrings during knee extension exercises in differing neurological pathologies (Busse et al. 2006) noted percentage co-contraction rates of 11.8% in normal controls performing isometric exercise (this increased to 20.5% when a dynamic sit to stand exercise was assessed- as would be expected in a un-restrained system where balance was required). When compared to a range of differing neurologic conditions the conclusion of this study.

Co-contraction can be physiologic or considered pathologic if it hinders function. Co-Contraction increases joint stiffness in response to environmental instabilities (Kornecki 1992, Osu et al. 2002) and greater control while performing tasks that require a high degree of accuracy (Smith 1981, Enoka 1997, Selen et al. 2006). It is variable and specific to tasks the environment and the training for that task. Co-contraction has been seen (Gordon & Ashton-Miller 2009) to give the greatest damping of movement at around 30%. This proprioceptive effect is a potential reason why there is a trend towards increased rates of co-contraction on attempted elbow flexion following reinnervation with nerve transfer. It is suggested that this is a compensatory mechanism for a re-innervated muscle which has reduced afferent connections and thus the higher motor programming is reaching out for more information on the movement- it thus increases triceps feedback via increasing its sensitivity or co-contraction to a near optimal level for this from 15% to 25%.

## **10.16 Study limitations**

The study design can be criticised in a number of ways:

- The retrospective nature of the study and the low rate of response when selecting patients introduces significant bias. We intend to introduce these assessments as part of prospective studies with this same model.
- The contralateral arm was only used for comparison of the peak force and sequential contraction- it was not used for fatigue analysis as well this was a failure of trial design - we had not envisaged the assessment would take the time it did and thus we did not

capture this information. The normal controls have allowed us greater freedom with subjects that were geographically closer and available for assessment under lesser time pressure.

- The selection of sEMG median frequency assessment of fatigue; although there is much debate surrounding the use of this myoelectric marker of muscle fatigue it is used by many experienced authors in this area (Mannion, 1996, Phinyomark2012) and has been shown to be reliable and repeatable (Rainoldi et al, 1999)..
- The protocol for elbow assessment was limited to isometric single position (ninety degree flexion in neutral supination) further dynamic and range, and rate of movement studies could be further undertaken.

### **10.17 Other factors**

The effects of chronic axonotomy, chronic distal stump denervation and the contribution of chronic muscle denervation were examined by Gordon (2011) and quantification of the contributions from each were made: First they demonstrate in a rat model that immediate nerve repair via a nerve graft does not lead to full recovery. Then the effect of chronic axonotomy was shown to show a decline in regenerative capacity relative to immediate nerve repair which is compensated for by motor unit enlargement. It was then demonstrated that prolonged distal nerve stump and muscle denervation have the most deleterious effect on regenerative success. This series of experiments has shown reduced contractile properties including that of fatigue to be linked with a reduction in motor pool, increase in size of the motor units and a shift to type II MUs.

The conclusion pertinent to this model of nerve transfer (where chronic axotomy is not an issue) *“chronic denervation of Schwann cells in the distal nerve stump and the chronic denervation of the muscle of re-innervation together inhibit the capacity of even freshly axotomized motoneurons to regenerate their axons and to re-innervate muscles. However, it is not simply that the chronically denervated muscles are replaced by fat (as is commonly believed) that accounts for the very poor axon regeneration and muscle re-innervation. Rather, it appears that, the chronically denervated muscle has a negative retrograde effect on the capacity of motoneurons to regenerate their axons”* (Bain et al. 2008).

There is evidence that chronic muscle denervation is not the prime factor that accounts for poor functional recovery after proximal nerve injuries (Fu & Gordon 1995). Functional recovery is limited primarily by the progressive fall in regenerative capacity of axotomised neurons and denervated SCs with time and distance. Loss of muscle fibre number and failure of re-innervated muscle fibres to fully recover their former size is an additional factor limiting motor recovery. Satellite cells may be reduced in number, ability to replenish muscle nuclei, and/or proliferative capacity (Anzil & Wernig 1989).

Beyond the function of the re-innervating axons the changes in the muscle are also obviously pertinent; the metabolic, biochemical, structural, physiological changes are well reviewed in Midrio (2006).

## **10.18 Summary**

Control and fatigue of human muscle is a feature of a very complex motor system- even more so when this system has been disturbed by a process of re-innervation. Simplistic assessments (as have been undertaken) will not identify a cause; only describe the symptoms. This study has

only started on looking at the symptoms and has only (intentionally) considered the contribution from the peripheral aspects of the neuro-muscular system.

In a review article on the history of fatigue assessment Enoka (2011) highlighted the central effects in fatigue and stated:

*“The activation of muscle by the nervous system can be compromised during fatiguing co-contractions and contribute to the amount of fatigue experienced by the muscles involved in the task. There is a great deal of work to characterise the impairments expressed in re-innervated muscle and how these vary between auto-re-innervated muscle (through natural nerve regeneration or through a graft repair) and muscle re-innervated by a foreign nerve (via nerve transfer).”*

There is indeed a great deal more work to do to move this work forward.

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13.

## Appendices

1. Patient demographics
2. Transcription of patient-participant discussion
3. COREQ form for the Phenomologic analysis

## **1. Patient demographics. Taken as a quote from BJJ Quick et al. 2016**

Case1 (NA): A 40 years old right hand dominant (RHD) printer sustained a left brachial plexus injury following a road traffic accident (RTA) 5years ago. There was an associated proximal humeral fracture, treated with plate fixation and a head injury, treated conservatively. Clinically, he showed little recovery for C5 and C6. Hence 5 months later, he underwent neurolysis and exploration of his left supraclavicular brachial plexus. Intra-operatively, there was nothing to distal stimulation for biceps either palpably or needle EMG, was noted. As there was no improvement in biceps function, 3 months later Oberlin procedure was performed.

Case 2 (TH): A 34 years old construction manager sustained a right-sided brachial plexus injury, and C1-C2 fracture in a RTA in the Carribean 4years ago. He underwent immediate surgery for C1-C2 there, and was later got operated at our institute for his plexus injury, following his return to the UK. Intra-operatively, C5-C6 avulsion injury was confirmed.

Case 3 (RR): A 70 years old lady sustained a partial cord lesion from spinal nerve injection with infarction of C6 neurones, 6years ago. Some residual biceps function only as single re-innervated most units seen under voluntary control and hence the decision taken to proceed to Oberlin's transfer.

Case 4 (GM): A 50 year old left hand dominant (LHD) builder who sustained a road traffic accident, motorcycle versus car, 6years ago, with multiple injuries, lung contusions and fractured Cervical spine, iliac wing fracture, inferior pole of scapular fracture on the left side. He also had an associated head injury. He had no Tinel's sign, no Horner's, nothing clinically for C5, 6 or 7 but preservation for C8 and T1. Intra-operatively, the plexus was found to be embedded in scar tissue with distal activity noted in supraspinatus and deltoid but none in biceps on stimulation. No recovery of biceps function at 3 months post-op (almost 6 months post-injury), prompted to proceed with Oberlin transfer.

Case 5 (AW): A 47 years old gentleman had RTA when his motorbike collided with a car at 30mph, 5years ago. His injuries were C4 – C7 and T2 transverse process fractures, T7 wedge fracture, left sided rib, clavicle and scapula fractures and a brachial plexus injury. He was operated for right postero-lateral corner injury of knee, four days post injury but his remaining fractures were managed non-operatively. Ten days post injury his brachial plexus was explored and an avulsion of C5-C6-C7 was confirmed and decision to proceed with Oberlin procedure in the same sitting was undertaken.

Case 6 (DB): This 24 year old RHD Carpenter was a motorcyclist who had a head on collision with a tree riding at 30mph, 6 years ago. He had multiple injuries including facial fractures, right humeral head fracture, C1 fracture and head injuries with contusions of the left occipital and frontal lobes. His brachial plexus injury consisted of the C5 and C6 avulsion injury. His head injuries prevented him from earlier exploration and reconstruction of the plexus and hence the delay in reconstruction. Because of this delay of more than 5 months, the decision was to go directly to the nerve transfers rather than exploration of the plexus.

Case 7 (FG): This 72 years old woman was sitting on her stationary moped when hit by a cyclist coming downhill at speed and thrown off her moped, 6 years ago. She sustained fractures of C6 and C7 lateral masses, as well as the T1 transverse process. She initially had a dense brachial plexus palsy involving the entire left upper limb, which was completely flail. Intra-operatively, C5, 6 and 7 spinal nerves were encased in scar tissue over a long segment extending to the upper and middle trunk. The release of scar tissue exposed a crushed and flattened nerve segment that was still in continuity. However, on stimulating C5, C6 and C7, there were no SSEPs recordable proximally and no contractions in the muscles distally (? avulsion). It was therefore felt that recovery in this spinal nerve would be most unlikely, and hence a staged nerve transfers were undertaken.

Case 8 (RA): This gentleman was in a motorcycle RTA 6 years ago sustaining bilateral fractures of the wrist as well as a complex fracture of the distal femur and right brachial plexus injury. He had operative fixation of his fractures and a month later was sent over to our unit for brachial plexus surgery. Intra-operatively, an avulsion injury to C5-C6-C7 was confirmed and staged nerve transfer was undertaken.

Case 9 (SA): A left-handed apprentice mechanic had a road traffic accident when his bike collided with a car. His brachial plexus injuries were only picked up a week down the line in fracture clinic and then a referral was made to our unit. He underwent an exploration where his injuries were characterized as C5 rupture and C6 avulsion and nerve transfers were undertaken. This was followed with a staged Oberlin procedure.

Case 10 (LC): A right-handed hairdresser who suffered a severe injury 8 years ago following a road traffic accident, motorcycle versus car sustained serious injury to his brachial plexus, (stable) cervical spine and also a hematoma within the spinal canal involving the spinal cord. At exploration avulsions of C5, C6 and C7 were noted and staged nerve transfers performed.

Case 11 (BA): This 49 year old RHD carpenter was involved in a RTA 2 years ago and sustained multiple injuries including intracranial bleed, facial fractures, lung contusions, mediastinal injury, left scapula fracture, left distal radius fracture (ORIF) and bilateral femoral fractures (IM nailing). After his initial stabilisation at his local hospital he was noted to have features of a left brachial plexopathy and had an inpatient transfer to our unit. At the time of plexus exploration, clear rupture of suprascapular nerve- distal part of which was not identifiable in the wound and evidence of a long traction injury of the upper trunk distal to take off Dorsal Scapular and Long Thoracic nerves was noted. Following the failure of functional improvement post decompression, nerve transfer procedures were performed.

Case 12(SP): A 19 years old sustained a left non-dominant brachial plexus palsy following a rugby injury 3 years ago. He underwent exploration 2weeks post injury, which showed avulsion of C5 & C6. This was addressed with nerve transfers.

Case 13 (MH): A 48years old right-handed gentleman had a road traffic accident, when his van hit another van at 60mph. He sustained pelvic and mandibular fractures, and injuries to spleen and liver for which he underwent laparotomy. He was in induced coma in ICU for 2weeks at his local hospital. His brachial plexus injury, C5/6 avulsion, was explored and addressed with nerve transfers 5 months post injury.

Case 14 (CM): A 46 years old RHD Carpenter was involved in a RTA, bike versus van, in France 3 years ago, sustaining multiple injuries including left distal tibial fracture, L1 fracture (managed non-operatively), head injury, left brachial plexus injury, axillary artery occlusion and posterolateral corner injury of right knee with associated fibular neck fracture and peroneal nerve palsy. Posterolateral corner reconstruction for his knee was performed in France. His vascular and brachial plexus injury were addressed at our institute 2 months post injury. At the time of exploration, he was found to have an avulsion of C5 & C6 that was managed with nerve transfers to regain shoulder stability and elbow flexion.

Case 15 (DB): A 38 years old right handed kitchen porter, cycled into a lamp-post 3 years ago sustaining facial fractures, minimally displaced left clavicle fracture, C7-T2 transverse process fractures, and left sided rib fractures (rib1, 2 & 3). He underwent Brachial plexus exploration 4 days post injury and C5-C6 avulsion and injury to Accessory Spinal nerve were identified. As a result, standard nerve transfer could not be attempted for shoulder stability. Hence, an attempt to repair C5 avulsion was undertaken, and Oberlin transfer was performed later as a staged procedure 7 months post injury.

Case 16 (BP): A 26 years old sustained a brachial plexus injury 3 years ago to his right non-dominant side following a RTA, motorbike versus metal fence. No other injuries identified. Three days post injury he had exploration of his brachial plexus and staged nerve transfers, first to stabilize shoulder at the time of initial exploration followed by Oberlin transfer for elbow flexion, 4 months later.

Case 17 (SB): A 44 years old gentleman had a RTA 3 years ago when he lost control of his motorcycle and sustained a polytrauma. His injuries included a transverse scapular fracture, acromion fracture, 1st rib fracture and brachial plexus injury to his right dominant side. Four days post injury he underwent an exploration of plexus where a C5-C6 avulsion was identified and a staged Oberlin transfer was performed 4 months later.

Case 18 (SP): This 49 years old gentleman crashed into a stationary bus whilst on his motorbike, travelling at 20mph 3 years ago. He collided on the left side of his neck/shoulder. A trauma review, radiographs and a CT neck did not reveal any bony injury and he was discharged from A&E. At follow-up in fracture clinic a day later he was noted to have focal neurology in C5/C6. Three days post injury he underwent a brachial plexus exploration that showed avulsion of C5 & C6 roots, and he had nerve transfers in the same sitting to regain shoulder stability and elbow flexion.

Case 19 (KP): A 57 years old gentleman came off his motorbike when was hit off by a car, 4 years ago, sustaining left clavicle, humerus and distal radius fracture, and infraclavicular injury to left brachial plexus. At exploration, next day following his accident, there was significant infraclavicular plexus injury in form of contusions to medial and posterior cords and avulsion of musculocutaneous nerve.

Case 20 (SW): A 25 years old was hit by a car, 4 years ago, sustaining a brachial plexus injury to his left non-dominant side. There He also had left humerus fracture that was fixed surgically at the time of injury. He was referred 4 months following his injury with signs of recovering Supraclavicular plexus injury but no biceps and weak triceps function. Hence, he underwent an Oberlin transfer to improve elbow function.

Case 21 (KC): A 40 years old sustained a brachial plexus injury to his left non-dominant side when his pushbike hit a lamppost, 5years ago. He had exploration of his plexus a week down the line, when an avulsion of C5 & C6 was confirmed. At the same sitting, he underwent nerve transfers to improve his shoulder stability and elbow flexion.

Case 22 (DC): A 33 years old gentleman had an RTA when his bike hit a tractor at a speed of 40mph, resulting in injuries to his right clavicle, multiple ribs and brachial plexus, 2.5 years ago. Following his initial management at local hospital, he was referred to our unit and underwent a brachial plexus exploration that confirmed an avulsion of C5-C6. He had multiple nerve transfers to improve shoulder stability and biceps and triceps functions.

Case 23 (PJ): A 41years old gentleman had a RTA, 4years ago, motorbike versus car, sustaining injuries to his brachial plexus on his right dominant side. At initial exploration, a long traction injury to upper trunk was confirmed and hence no nerve transfer was undertaken. However, following poor recovery over next 6months, it was decided to proceed with the Oberlin transfer.

Case 24 (CB): A 37 years old gentleman had a RTA 2.5 years ago, when his bike was hit by a car, resulting in right brachial plexus injury. He was referred 3months post injury and underwent brachial plexus exploration and nerve transfers to improve his right upper limb functions.

Case 25 (TB): This 52 years old gentleman had a RTA in 1995 when his bike was hit by a car. This resulted in comminuted humerus fracture and injury to musculocutaneous nerve on his right dominant side. He was referred 14 months post injury for his nerve injury and underwent an Oberlin procedure.

Case 26 (IB): This 41 years old lady was a front seat car passenger that was hit by a tractor, resulting in a left brachial plexus injury. She was referred the same day and went a brachial plexus exploration to confirm C5-C6 avulsion and had nerve tranfers to improve upper limb function.



## 2. Transcription of patient discussion group.

KJ -Everything is going to be confidential, no wrong answers, no names mentioned. Very much an open forum if you have any mobiles please put them on mute. If you feel you need to get up and have a break just get up and go.

Just a recap to start with, shall we show video which most people have already seen in the questionnaire in the beginning.

HB - The focus is on the actual elbow bend and straightening, this is the movement we want you all to concentrate on because the surgery that we have looked at that you have all had is to make you be able to do this movement. You've probably had or may have had other surgeries as well, other muscles or nerves but this is our focus today. We know it is very much not a straight forward injury; it's a very complex injury.

KJ - So to start with do people want to say how long it is that they have had their nerve injury or nerve surgery in the elbow? Just to give people a bit of an idea of where everybody's at, that might be a good way to start.

TB - My accident was June 1995 and I, do you know what I can't remember if it was 95 or 96 I had surgery but it was around then. That long ago I can't remember if it was late 95 or early 96.

KJ - Tony, when was the nerve surgery in the elbow?

TB - That came because I was in hospital for about a month and they didn't diagnose it until the day of discharge. The physio asked me to move my arm and I said I can't, she ticked me off for being a bit lazy and I remember one of the nurses saying stop making a fuss and lift your arm up. I said 'I can't, I can't' I have a plaster cast, and it was on the day of discharge. One of the consultants said medical plexus refer him on to Rolfe Birch and so then I was referred and then I had some tests. So I think it was the actual 1<sup>st</sup> operation, pretty sure could have been that year so I would say 1995.

KJ - Ok, so you had it quite a while ago

TB - Yeah

KJ - Anybody else as long?

LJ - Mine was October 2015, my surgery so that is quite recent compared to yours. I had a nerve graft on my shoulder and the oberlin transfer? When I first had it I think it was those 2 fingers just very weird, hyper sensitive

TB - What the first 2?

LJ - yeah, I had those 2 i don't know if that was to do with the shoulder or the biceps

KJ - So you had that experience after having the oberlins, the sensitivity? Or was that before?

LJ - That was I can't remember now, if after the accident or before or after the surgery

KJ - but particularly the index, the middle?

LJ - Yeah yeah, and it still don't feel - they feel much better - but they still feel kind of rubbery. A little bit, but much better than they were.

KJ - Do you feel that affected your recovery from surgery?

LJ - No I just, it was just there, that was it. Just carried on really.

KJ - and Jenny you were saying your..

JT - Yeah 14months ago. I had key hole surgery and then the musculocutaneous nerve got damaged in my shoulder, I'm a PE teacher as well so... devastated

TB - What was the keyhole surgery?

JT - I had dislocated shoulder, and they were doing keyhole up here. For some reason, nobody's really sure what happened but it took them 9/10 months to diagnose that. November, so it's been 3 y ears since the keyhole, ongoing really since injury.

TB - Sorry I know it isn't very interesting for you but it's interesting for me because having a bit of a roller coaster ride it is reassuring from somebody else's as mine was the same nerve trunk that I have been left with

JT - Yes it's still ongoing, still experiencing quite a lot of pain at times so that's the challenge and the frustration as a PE teacher that I am not patient. It's not my strong point

6.10

KJ - is pain more since having since the Oberlin or was the pain..?

JT - No the pain was horrendous before. It's changed and it's definitely a different pattern, more down the UN side.

TB - Wondering if we have the same pain, so your pain, when you say the UN

JT - it's shooting down this side, these two fingers and at times it's like I've got a really tight elastic band.

TB - I do get pain, but not that sort of pain

JT - Yeah, and I just want to stretch the fingers out because it's kind of nice feeling

KJ - do you experience that pain as well?

6.17

SB - Yeah it's quite stiff, but a similar sort of time, my accident was about 18 months ago. I had, was it the Oberlin that they put back in and the AN because I pulled out 3 of them, C5 6 and 7. I find the pain worse in the cold, you can get up in the morning, I find stretching out does help getting going in the morning, because there is less the circulation and movement there you end up doing those things to bring it on yourself.

TB - How did you do yours Steven?

SB - motorcycle accident

TB - It's interesting , who was motorcycle ?

TB – Mine was a pushbike. My injuries were sustained as I was T boned by a car and went in to the side of it, where I was holding the handle bars my arms acted like blunt force so they all sort of, my joints took the. Mine wasn't caused by landing on my shoulder which I believe is quite normal, no I can't remember my accident.

SB – I can't remember my accident, I've hit the car and this bit stretched

TB – Mine I don't remember, I can imagine your arms acting like platforms

KJ – Does pain seem to be quite a common theme with quite a few of you?

PA – it's changed over time, I mean at the very start some of the pains were horrific but you become used to it a little bit, like anything. You understand your body as well.

PA – You cope with it

09.10

JT –are you still on medication for that? Still on your gabapentin?

TB – I'm not, is that a pain killer? I don't know what that is? No, I don't think I ever had that anyway. Mine's a bit of a tricky one because I've got a bit of arthritis coming in to my elbow because where all the joints got compressed and the soft tissue sort of wasted or withered, pushed out. But because I over compensate with other muscles, is it brachioradialis pick me up with that muscle. My elbow sort of moves fine, but come after a few hours or a tiring day I then get arm ache, I get a like a tennis elbow and some! And tennis is one of my sports which I have had to stop because if I have a knock around which I do now, I just have the odd 10 minute knock around but then I pay the price and if I hit a couple of gentle serves then that's it.

JT – agrees in background

KJ – Do you feel it's more over use than compensatory muscles?

TB – Yeah, tennis elbow sets in and I'm in trouble, when I was playing tennis moderately regularly there came a point that I was in so much pain that at best I could use a pen, just couldn't use my arm. Had it in a sling, so it was knackered. But now, I have stopped tennis if I have a busy ish day, because I still lift things, I still do things as normal. I forget, because you do. You just sort of get on with it don't you.

JT – I am really struggling with that, and that was part of the problem with my bicep didn't look like it was doing anything for ages, but all my other muscle groups was compensating and my brachioradialis is still one of my biggest problems. Still! And uncomfortable, by Friday just lifting the arm on Friday is just exhausting, throwing you hair and all this kind of regular tasks.

GP – holding the phone, using the phone for any length of time. I do it deliberately with the weaker side. I keep using it, but it is being locked in that position for a length of time and then it will start aching down the forearm.

JT –and that's really when I knew there was something wrong with my bicep was this was getting massive and this was getting smaller so..and it is really dominant on this side.

TB- do you get creaks and cracks ?

JT – I don't get creaks and cracks but the knocks in that muscle are huge so lots of massage. Heavy, aches.

TB – I now find that if I have a busy day I get not that painful it's really not that painful, but I get a tiredness. I don't need to take any pain killers for it, it's uncomfortable but I can feel it, I have got it now and it starts sort of around here and it goes up here. This is the bit that I will sit there, normally when you massage yourself you don't get the benefits do you? And I will sit there and prop my neck, it just gets me here. I don't know what, you probably have more knowledge of that. I don't know, because that seems like a treatment. It's not really life stopping, I still carry on it is just uncomfortable.

KJ- are any of those symptoms you've mentioned attribute to having occurred following the Oberlin surgery, as they changes occurred and started to get regeneration in the biceps do you feel there is any particular sensation or symptom that come with that regeneration of muscle that?

SB – you're talking about what, twitching and things or sensation as in fixing?

KJ- Yes, so as you. Following a nerve surgery I don't know if generally when you've first started seeing any changes for instance, did that vary amongst you? When did you first start seeing any change?

JT – July, I was done in November. Quite a few months, cos I was like it is never going to happen.

KJ – And what was different?

JT – I had to absolutely concentrate on what I as doing try and switch off all the other muscles to try and get it to work because everything else was firing instead of it

KJ – did you feel any sensation around there, what made you feel something was happening. What drew you to the attention that something might be first happening.

JT – It was coming in and being attached to, that was the first bit when you're attached to you can see the bio feedback was massive for me. It was then being able to concentrate and see all that sensation and concentrate enough to feel the bicep was working, rather than just letting the other muscles take over. And you could then feel bicep, but having that bio feedback was just massive.

KJ – Would you agree with that?

P A– We heard it here, I was trying to ask and I couldn't get it. We haven't got that locally with my physio and so I had it put on here and as soon as you try and get that movement, then all of a sudden get that beep and you know that's what you have to do, but when I've gone back I can't do it again. Without that feedback once you've isolated that movement it's just something beeping to let you know you're doing it, and it worked.

14.47

KJ – And that was the first time you were aware of anything changing?

P A– Yeah, getting hit in the right

TB - Mine's been coming back a bit from that, this is even when it wasn't diagnosed that I had any problems with my biceps but when I was in the ward and it was one of the nurses that used to come, because my arms were mashed up anyway and was in plaster. It looked like a scene out of a carry on film, that they had to just keep my limbs moving, just so they didn't seize up. The guy would come every day and just gently move my arms up and none of us knew that I had a problem with my nerves that I used to get some real tingling sensations going up and down my arm and it was a real sense of relief. We hadn't realised that I had a problem, but that was quite a comforting thing. So there was obviously some sort of conduction there. Although my arm didn't work at all. As he stretched it I could feel a sort of tingling down there, so there was obviously something

KJ - it sounds like Paul you mentioned local services quite different, everybody experiences of therapy are very different. How often do you feel would be helpful to be monitored after the surgery, or just been seen. What do you think would be helpful in the scheme of things, from a rehab point of view, in an ideal world?

SB - I haven't had any of those, until we did that induction stuff. Nobody really plugged me in until they did in the first place they give me a? I didn't have anything afterwards. What I started noticing was in the pool first of all, I wasn't moving but it would go in. it wouldn't be a smooth movement, but yeah I noticed I could do something and I had to really concentrate but out of the water, with gravity there was nothing there because you can't push it on against the weight, and it was completely wasted away. But when you are in the water, it was like oh yeah I am doing that myself. And as rubbish as it was and as small as the movements were I am bending my arm doing that and I was getting a little bit of abd as well.

KJ - so you talk about the water, was it hydro therapy ?

SB - no just the swimming pool, again to help with the range of motion because obviously you can bend by the side and that's a good place to do it because I could stretch myself and all that sort of stuff, but that's when I started to notice it.

PA - I has the same thing here in the pool, I had hydro-therapy and I couldn't do any movement with my arm or feeling, and slowly it was the best feeling in the world when you see that move but so much pain there I couldn't actually feel what movement it was, it just moved slightly in the water and then it got better over time but the bio feedback when it gave me that message. Being able to send that message out of the water, that is how I was able to isolate it.

SB - I did wonder in the first place because I was on a lot of pregabalin because they were saying, because there were twinges first of all, because I was on a higher amount, I couldn't feel it because it was stopping the nerve sensation to an extent so I wouldn't be aware of the sensation of it kicking in because, I just wondered if that was the case? It starting to go, were the sensations there all along?

KJ - when you say sensations, do you mean deeper sensations or touch?

SB - well it was always a sharp shooting pain, but I have had them from the beginning so I didn't know if they were fixing pains or just pain that was there.

TB - did any of you, were any of you strapped to a tens machine? electric shocks

LJ - yeah the stimulation machines, yeah. I used them daily

TB - I had mine strapped to me for quite a few weeks

KJ - did that help?

LJ - yeah I walked I used the one that Anna showed me to use and I've got a private physio now they gave me another one, but that's more for my shoulder. My bicep came back quite well actually, so that's more for my shoulder at the moment. I used it on my bicep to start and I had to really yank my wrist up to get there.

JT - whereas I had to really rotate (supinate) to try to switch this one (BR) off more.

TB - I didn't get any of those spasms at all, mine were gradual. All I did get was when I used to go to physio because my elbow in bits, my arms wouldn't bend for that reason but I remember they did some hot wax treatment, and just dip your arm in wax and they wrap it in bandages it was like molten metal, I couldn't put my hand in it it was too hot, they said it isn't that hot but I said it is it's really boiling. If I didn't have a beard then, if I was unshaven I sort of face felt a porcupine, needles coming out of it. Mine was really subtle; I didn't really have the spasms. If I was eating dinner, because eating is really personal isn't it? I used to have my hand on the table and my hand would work at that point, I used to just go down to my hand and sort of do it that way. Eventually I used my little index finger and just gradually like that, but I didn't get the spasmodic, just sort of gradual. You just put up with it, didn't pay much attention. I used to get a lot of the pins and needle pains.

LJ - Hypersensitivity? arm face?

JT - I think I don't know if I had done that earlier I might have been less frustrated, I didn't think it had worked so I was kind of getting really despondent about it and I don't know if that had been earlier and there had been a little sign I don't know if that would have helped.

GP - did you do a week at Stanmore?

JT - no

GP - I did, and that made a huge difference to me doing the week

KJ - how long after your elbow surgery did you have the rehab week?

GP - 2 months, had surgery at end of August and then end of October I did the, and that was the first time I came out of the sling,

TB - I had a hunter sling, do you still use that?

GP - just a standard sling. Nothing spectacular

KJ - yeah very similar but softer than hunter tape

TB - bit like a strait jacket.

KJ - don't think any are comfortable,

GP – that week in Stanmore I had the tiniest twitch of a movement and I had the tiniest and from that point onwards it is easy to or it made sense then that everything was going to work again, that was my intention to make sure everything worked again.

TB – how long ago was yours?

GP – 2014, I pay for physio now and I have that every 3 weeks that makes a huge difference keeping everything mobile. The biggest problem I found was the stiffness, you get stiff and then you can't do things and then the muscles get weaker so just having that release from a physio. Not so much the exercises but just getting that release makes a huge difference from the shoulder down through in to the bicep and so on.

TB – my wife, in bed every night does massage my forearm, my neck. It is a nightly routine because I am creaking and cracking. It is aching quite a bit and it is not the same if you do it yourself, she says do you want me to do your arm? She really gets in there the forearm, my neck.

KJ – lots of people nodding there,

JT – I find it hard with the stress and the stressful jobs oh my god the pain, yeah definitely. It tightens up and is difficult managing that. I have real tightness even trying to straighten my arm is a real challenge, especially when you elevate it and I weren't really sure what that was, real tightness. And it felt like a real pulling, and it still does. But only when I am lifting it above, but it has got better over time

KJ – so tightness was there when you first started recovering ?

JT – yeah and a real pulling, it is coming back slowly but can't lift my arms above my head without it being bent without that pulling sensation

TB – can you show me?

JT – I can get to here, but I can't do it straight. Now it starts to pull here, a real pulling but I can do it bent.

PA – I get the same sort of thing but because I've had tendon transfers and they are wrapping stuff around different places you don't know whether it's the muscle that's tight or as the tendons have been wrapped round you don't know if that was the pulling.

TB – have you got scars?

JT – yeah down to about here.

TB – my scar used to pull until I took some of that scar tissue out. The scar starts here but that was like an electric cable during one of the surgeries I think they removed some of the scar tissue.

LJ – do you have massages to help with it?

JT – I've tried but just myself really. Acupuncture also does help.

TB – yours is quite young, and mine is quite old but I can lift my arm now I used to dive, look forward to diving but couldn't stand up straight because obviously I couldn't do it.

JT – I've tried to teach badminton and that's been frustrating as just can't do it.

TB – I think we are quite similar and that mine has got better over the years it has

KJ – it's interesting just hearing you say the things you can't do, you could do previously or you are doing it in a different way. Just bringing us on to how you would classify whether the outcomes been a positive one for you how would you classify that? How would you recommend that we assess that, because at the moment, medically we talk about MRC grades, we talk about questionnaires which as far as you've done, you will talk about lifting weights kg and I don't know, how meaningful is that to you? As a guide to measure success?

TB – it has worked for me but not as a bicep because I have just used other muscles, I can lift quite heavy weight now it is difficult to do that. Call it a preacher curl where you actually do that, I will do it like that and I will do it differently but I can lift quite heavy weights. I have got a bike shop and get bike deliveries and lift them, if I am taking something down from somewhere I will get so far then I will change my tactics

KJ – and that is what the majority of people have said, wrote in the questionnaire that they had realistically expected to go ahead with the surgery and be able to bend the elbow and lift some weight. I am trying to interpret that and is that different to how everybody would interpret some weight

JT – I find the weight question difficult. I think it is more about functionality and daily life style I think. yeah and it's difficult because pre surgery I just wanted my arm back, and I don't think I had any perception about what that would mean afterwards. I don't think I had any idea about whether it would mean full function or not. I just wanted my bicep to work again so I wasn't really concerned about or hadn't even thought through what that would mean post-surgery.

KJ – Your expectation was to visualise..

JT – yeah, and I don't think I had even thought that it might not be back how it was. I don't think I had even had any expectations.

KJ – it would be harder to classify that in more detail ?

JT – I didn't think that I would have thought through, oh I might not be able to do that, might not be able to do that. I just thought it would be fixed

KJ – you hadn't thought to that level?

29.34

TB – when I had mine done mine was with Rolfe Birch and I remember him in Stanmore, and it sort of a bit like young Frankenstein, all these registrars and doctors and he was saying to them, what do you think the success rate is and they were all saying 5% 10% and he said 95% of these operations will be successful. But I thought originally I was going to have a bicep and I think oh I have got my bicep back, but what they done is fixed my ulnar ? nerve so I have got a clip of a bicep

there but it doesn't work as a bicep it doesn't flex when I do that and it flexes when I do that so in terms of bulk I look relatively normal, but it doesn't work as a bicep but so if you measured me this way it is still weak in that.

KJ – so by using that form of measurement the MRC like you say it's not necessarily a true measurement of the success for you. Am I right in thinking that everybody's definition of success is probably quite individual?

SB – yeah, if you put down specific measurements you are limiting people, you could think I am done but do 20 more depending on technique. You are actually not helping in some cases or with other people it might be numbers by putting things down like that, when you are not sure yourself or could be the outcome, could be the fact that

HB – I wonder going back to what you were saying Jenny you mentioned the word function and about a measure of function and you all seemed to nod at a similar time, does anybody have any ideas about what might be a good way of us to measure functional for you to feedback ?

LJ – I think general day to day lift, so like job side of things. getting the kettle, getting the dishes down, brushing your teeth, anything like general living if you did functionality like that

JT – I think the repetitive tasks are difficult where I still find, like everyone saying you get tired but I think to do one flexion, one lift of the kettle but if you are doing stuff repeatedly that's when I find I struggle. And I don't know whether the definition of functionality there was flexion and I think that is what I didn't have any concept of that would be there.

TB – Jenny you said you were right handed. Who of us has the injury on the dominant side? You are not, because I am right handed. I mean at first I started to do everything with my left hand and tried to play tennis and didn't enjoy it. I would give you left handed lessons,

JT – agrees in background

PA – it is going to be different for different people because some of you have lost one of the nerve functions but not everything, you still had some. I had total loss of the arm, it was just hanging there no ability to move it at all not flick one little finger, so the arm is just dead like this. Just hanging down, trying not to fall over all the time because you have this heavy weight. Me, a successful outcome would have been to measure, all I wanted to do. Spoke to another guy I knew 10 years earlier and he had his arm cut off because of the same situation. Just to move it was a reasonable outcome, imagine if you felt that you want to do a lot more with it so to measure it to a person specifically to what is a realistic outcome, and maybe based on as you see so many different Scenarios you could give the person a realistic idea at the start of what they can expect, because some people will have unrealistic expectations everyone different. But knowing what the likely outcomes you can't make any promises but give them some idea that was never really there at the start.

33.46

JT – That was never really any conversation about the outcome, so I just thought I imagine it isn't going to be back to that (normal)

KJ – What information did people get, if any?

PA – more from other patients actually and the nurses, the nurses seem to know and the physio seem to know what's going on and the consultants are really busy and I understand that they have got to do their thing, they understand what they are talking about but a lot of the time they are talking in Latin terms but yeah I found out a lot from speaking to other patients in the jubilee ward and the people with similar injuries, they were telling you stuff on what to expect and what can happen. I found out more from them than I ever got explained in technical terms.

TB – I was explained that this tens machine was trying to train my brain to get my bicep to work as a bicep and I think I wasn't unhappy about anything, but in hindsight I was sort of feel that I was led to believe that a bicep would regenerate as a bicep, but what's happened is my bicep flickers with my ulnar nerve which is fine, I just look sort of quite normal. I won't ever have army guns but I have got a bicep that I use, so you just live your life.

GP – is that to do with the way that you've dealt with it and had say full on physio for say 3 months, would you be any different?

TB – I did have physio, I had the week at Stanmore and then because I live in Hertfordshire we had Herts County Hospital which had a physio Dept which I visited every day. 5 days a week for several weeks, that was a few months. But it didn't work independently, it picked up the current from the ulnar nerve but it didn't ever work independently as the pain subsided as I gained more movement so on and so forth my life became better, and when I do things I look quite normal. I do pay the price, not in a serious way but in a pain and achy and up here but I do do things quite normally and like brushing my teeth, if I am tired I will just hold my index finger up. I will carry on as normal, pouring something at the dinner table if I am tired, I normally just prop my arm up.

KJ – again, it's function that is the common theme.

TB – I am happy with mine because I am used to it.

KJ – you was just saying Gary about the therapy input you had, you feel that that made a difference?

GP – yeah, it makes a big difference for me anyway. I just felt that I could see the progress I was making and that made me more determined to carry on more progressing. It might be a mind-set thing but it was just always, see the physio and feel that something's changed, get on again and go again and know that in 2 weeks' time they are going to look at me and think right let's go again.

KJ – Did any of you have functional mile stones in mind do you feel, and it sounds like what you say earlier probably individual, do you think you all had your own functional milestones?

GP – yeah, being able to drive was the first one for me, as well as the movement aspect, being able to use the gear stick and then put my hand back on the steering wheel and gear stick, those sort of movements once I got those without having to worry and then after that the milestones have been just some personal and trying to, my ultimate goal is always that nobody that doesn't know me would know that I have got an injury.

TB – I am there, because nobody knows that and they just have no idea and it's sometimes, where was I when he picked me out of a group of people and said you're a large person, I need some muscles to lift and I thought oh no, but I did it. It was carrying a plant pot for an elderly lady, I was able to do it because I could lift it that way so that was alright.

GP – I make a really conscious effort to use my weaker arm far more than I would have done previously because it is not my natural arm to use.

JT – but I am avoiding it, don't know if that is good thing not using it. Writing, marking kids work. Really struggle to do, the pain increases.

TB – at the beginning my right hand looked like my left hand

GP – I swapped sides of the mouse, as I normally use it with my dominant hand but I used it with my left hand and I do a lot of mouse work and CAD drawings, I use a small mouse as well and that just doing that a lot makes a real difference.

TB – I use a computer all the time but using even just a touch pad because my arm is rested on the desk and after 10/15 minutes of using the mouse my arm is absolutely knackered

40.30

JT – yeah mine too

TB – really tired. Sometimes because I run a shop and can only get work done when I'm dead and I have my little laptop tray and I am undisturbed half an hour do my work, but then in bed with my elbows rested under the pillow I am all nice and comfortable but 20/30 minutes and I'm achy.

KJ – so functional tasks do require endurance don't they?

TB – yeah when I am not moving my arm but I am just doing this..

40.52

KJ – can I just clarify, have you all got hand function have some people not got full hand function as well?

SB – My flexors work but extensors don't – when you guys are talking about function for me it was sort of right round my right hand more than used for everything and learning things again, so your perception of function is a little bit different

LJ – you adapt

SB – you want maximum outcome so you learn how to do that again so it is a little bit different. You can do everything, you find a way. You can do what you want to do but you are doing it in a different way.

KJ – life style, all your injuries are different. And what you said earlier on, everybody's goals are different because of life style and all injuries are different.

SB – Everybody's markers are different. I won't be able to write left handed because I was right handed before

HB – what would people say would be their minimal important difference to make seeing as we are on that kind of subject.

What would be the minimum thing after the surgery that you would expect?

SB – well your arm not there or having heard other people who have had it amputated then any function is better than none so that is kind of just the starting point, if it doesn't work.

KJ – there are a few nods there

TB – I think my problem was personal opinion, I was slightly different in both my arms were hindered in my incident, this had ulnar nerve injury which repaired itself, but that was from wire, screw both my arms were hindered. I think being right handed this arm didn't move so I couldn't touch my face and it is not relevant to this conversation but yeah mine was the very thing I wanted was just to be able to go to the loo and take care of myself and not have my wife and my friends carrying my wee bag around and stuff, I just wanted that. So personal maintenance something I could manage

42.25

GP – one of my goals was just that I could wash and dress so I could have learned how to do everything left handed for a start whilst I was strapped up

TB – see, I couldn't do that with my left hand.

GP – just getting that back so I didn't have to rely upon it or anybody.

TB – there was one occasion where I was on the loo, then came the moment where I had to seek some help as fractured my foot/toe by kicking the radiator I was so angry I couldn't take care of myself and I that was my thing, I just wanted to do that.

PA – Dignity.

KJ – is that different experiences pre surgery and I think generally speaking people said they didn't get that much information so their expectations were

GP – I did, I had plenty of information and I knew what the possible outcome was so I was happy that I was fully briefed on what the likely outcome was and what the possible outcome was and what the downside was

KJ – do you feel your expectations before and after were similar

GP – no, because I was told I might get 95% of my function back but it's still the fact that all I wanted was some function. 95% was that wasn't really relevant it was just to have that function that I didn't have an arm just say beside me.

KJ – so thinking about your minimal change?

GP – yeah, it didn't change that,

KJ – other people that did have different expectations either pre surgery or post-surgery or they've changed, it sounds like quite a few people's expectations changed? Because of the information, am I right in saying that or not?

LJ – I think I was just a little naïve I got the information was that I am having surgery, like a broken bone it kind of meant that you get better and you expect it to not nothing happen for ages and then still keep going and going and going still trying to work that extra little bit, I was very naïve thinking next month I will be fine

JT – yeah I agree, I didn't realise the length of time I think that and the frustration the effect would be, oh I have had surgery now it's going to work, it didn't and I found that quite frustrating.

TB - I was told, certainly all the way along regeneration would be ages and ages and ages. You know you are looking at a couple of years

JT - think I was told but I don't think I believed it, I was told I was going to have to be patient, but I thought I don't think so

KJ - I think it depends your mind-set as well, that all comes in to it

TB - I was quite prepared for it and was happy to make those little advances, and I remember the day that I could touch my face and just yeah I was quite patient. Mine is slightly different because I had other injuries which it was a month before they diagnosed mine, 3 weeks before they diagnosed mine.

GP - think one of the things I have found is not to rest when you get to, you know you don't have milestones necessarily but when you get to the point where you are functioning, and think oh I am functioning now it is then pushing on then, to keep going and going and going. That's one of the things when I am doing something fine, I will then think right try something else. Maybe change things

TB - I have got used to it now, but every day I will think I will do something, whether carry some shopping on this arm, I can make a bit of traction and pull my elbow apart give a bit of relief. Everything I do is still taking care of that, but I am so used to it and it is second nature and I am quite happy even now I am feeling pain up here but I am used to it.

PA - you have got to be positive,

TB - yes it isn't irritating me anymore, tennis elbow when that comes in that is quite painful and it is a bit irritable. They did offer to put a new elbow in, but that carry's it's own complications so I refused that. That is not to do with the oberlins that is to do with the arthritis, I am happy with where I am at.

KJ - it sounds like function on an individual basis is the key way of measuring that difference in improvement that has to be individually tailored, but also movement as well because at first you did say you wanted to be able to wash yourself, thinking about dignity but then a few people said just to have movement and it felt important for still to look at range and strength but our ultimate goal being function and what we need to break down particular tasks, what we need to do to achieve those. So we need to also look at pain levels and need to look at compensatory different muscles working.

TB - I think that is the key, certainly with me. The biceps still measuring the function is not strictly true, we can all lift a bit, do a bit in terms of kilos but it is how the nitty gritty of how that function is measured, it is not measured as bicep because it doesn't work as a bicep.

JT - It cheats

KJ - in isolation?

TB - yes. I have quite a well-functioning arm and I am quite happy with it and my disabilities they are there but they are not..

KJ - it sounds like everybody is quite different, different muscles are taking over for different people so is there an element of education about having that awareness of what is working and what is taking over, or do people feel they..

JT - I don't know doing the biofeedback more would help, because your day is so busy at times you don't think and I think as long as you are in a habit then you are almost having to undo that habit to make the bicep kick in again and it is having that space and time to think more often am I using my bicep here or is everything else working and that is quite hard when you go back to everyday life, and you are back in work the problem is then you are just reinforcing the habit all the time. And you have got to have that time to try and break the habit otherwise it is just going to continue to take over.

JT - have they said your function will come back?

52.33

JT - yeah, it is coming back but it is just not everything else is just kicking in too much so I am probably not using it as much as I should do

TB - but is yours connected to your ulnar nerve?

JT - yeah it is my ulnar nerve

TB - do you click a finger and your biceps contracts?

JT - yeah. Its vain but when you talk about looks you see it come back you can see the atrophy.

TB - I can't go to the gym and do curling as mine just doesn't work like that

PA - Its quite amazing how quick your muscles waste away. They did explain some stuff that your muscles are going to waste away in 3 months. And you can't believe, I was a really big guy and massive biceps and they just disappeared to bone in 3 months and they were gone. You do become very conscious of that, and vain, my hand just wasted away. I was aware of an imbalance in my body.

SB - the information of the in balances still going forward, you developed ways of coping. But you kind of found that out, looking back thinking about that, they said if you are going to have to work these muscles or use your body in this way or how to compensate, information on that would be good.

JT - and it is now, knowing whether I should still be compensating or actually now I should be using it, does that make sense? I have got used to opening doors using hips, bum foot everything I use now rather than use my right arm and I don't know whether now I should actually be trying to use my right arm, it is just now a habit.

KJ - that is hopefully something therapy will help with.

GP - I make a conscious effort to use it and try and make the movements that I do as close to what they used to be. Like taking a coat off, using your right arm. I can now just get it off just about normally.

54.40

TB - take this as good news, I am 20 years down. I use my right arm normally really honestly, sorry I will rephrase that, I do pretty much everything as I did before with a little help from my index finger on my left hand. The tennis and stuff I have had to stop

JT - that's what I worry about, I don't want to have to stop

TB – I am quite fortunate as I am a cyclist and I still ride my bike, when I had the tennis elbow I had difficulty changing gear, both on the road bike and mountain bikes but one of our customers has a BP injury and he got some movement back but we have adapted his bike. I do pretty much everything I did with a little help.

KJ – you are compensating to a degree but you use the word normal, your definition of normal is different

TB – I can still brush my teeth, still with personal cleanliness, ride my bike, have a little knock around at tennis, I can't do anything too.. But you know I am 20 odd years down the line and I'm sort of ok, what I do suffer with is just a bit of arm ache. So long as I don't overdo it, if I play tennis then I will have my tennis elbow and that will be 4/5 weeks do I tend not to do the sort of hard exercise that I can still lift and go about heavy duties with the help of my index finger, brushing teeth, pouring out water and even drinking my coffee. Sometimes I get a bit tired but you just do it, but my life visually is quite normal.

56.44

KJ – we need to measure the fatigue, which is a key thing coming through.

HB - And if there is difference, like Jenny you were saying repeated activity but then you were saying Tony that when you were sometimes when you have been holding your arm still for a long time, is there a difference between the 2? How would you define that?

JT – I don't think there is, it is like if I have to hold a tray I am still very conscious. I often forget, and go and tell people to sit down in a restaurant, and then really worry because I have to carry the tray. Even a little way and it begins to fatigue, so it isn't just repetitive stuff. Having to hold stuff, even stationary it can increase quite quickly.

TB – I am just trying to think, the fatigue comes from working the mouse and the touchpad. It comes quite quickly in fact quicker than physical, if I was lifting bikes and doing stuff and that comes along quickly.

GP – the struggle I had was fatigue full stop. I would, not so much in the muscles but post operation I would be doing normal work and then all of a sudden the brain would go blank and couldn't think and that's only just 2 years.

JT – I thought it was just the medication - my memory is awful

PA – what is the actual physical fatigue and what is the meds because they just, you can't isolate as you get both and they sometimes come together. You don't know what's what. You just know you are doing strange things and people look.

TB – yeah, I don't have meds.

LJ – I never took any meds

KJ – but do you still experience that fatigue?

LJ – yeah, a lot of fatigue. My accident was July 2014 and my op in October

1.00

PA – it's interesting because once you explain it to people and you put it down to the medicine. When you are in pain all the time as well that wears you out as well.

LJ – I don't have the sharp pains that you have all had, so you probably have meds for that. I just have like an achiness and that just drains you after so many hours. You can't take it, you have to just go to bed to sleep or

JT – I thought there was something wrong with me, I went back to the doctors and said I think you need to take my blood. I thought there was something wrong with me, I had no idea that that sensation was going to be, I thought I was suffering with something. And it was just, that is what it is, that is what it is like.

LJ – I do 2 days' work a week and I start off doing half days and I was dead, now I do 2 full days a week now and I am still like quite tired, I need a nap when I get home but I can do them now. And I couldn't do that before at all. I do removals You can get better but you will still get tired.

SB – I was trying to get back to work, and asking is it the medication making me like this?

KJ – so trying to get that next step in getting back to work?

SB – exactly, and then you move the goal posts. I wanted to be able to it, so was doing half days and now I am doing full days. It is that side of things that you quickly learn....

KJ – and finding an employer that is open to that?

TB – if I could invent something that would make me comfortable at the end of the day I would invent some sort of contraption that would hold my arm right through to my palm up here, like putting your arm around somebody, that is a lot of relief to me. Sometimes I just splint my arm up, I have got some crutches and so every now and then I have a prolapsed disc and put 2 of them up there and I just rest my arm. That offers quite a lot of relief, don't know if it is to do with the nerve you get a few pins and needles when I stretch the nerve but it is just nice relief. Little things like that have found which never really shared with anyone before.

KJ – it is interesting to share, and hopefully today you have found

TB – Sometimes we have been shopping and I am with Sian my wife and I have asked, can I put my arm around you. Literally will just walk like that and it is so comfortable and I am doing it for medical reasons not anything else, I have been with her for 30 years and I wouldn't change her for anything but ....

KJ – again, it's pacing isn't it?

TB – yeah, but that offers a lot of relief suspending my arm up like that. It is just lovely.

KJ – There is one thing I wanted to pick up on, the wrist. You are still bringing the wrist in to activate the movement, or you were at the beginning?

LJ – yeah, at the beginning I would do that just to get flickers and I did that with like a little stim machine, I don't know if you had those? You would put them on and then eventually take stim off and then do it and then eventually work that out by constantly keep working that muscle that you have got to connect your brain to that muscle, takes a while but yeah that's what I keep doing and then it takes over.



1.03

JT – my own personal biofeedback would have been nice. Would have given me positive reinforcement of actually you are getting it right is quite hard and trying to make that connection.

GP – the machine is good though because you can see it flickering then can't you when you have got the pads, it will give you that jolt and then you really feel that it is benefiting

KJ – has that affected people wrist movement at all or? The action of having to bring the wrist down to activate the bicep has that affected your wrist function?

JT – I find turning keys in doors still really difficult,

TB – I am ok with keys and screwing a screw driver I can do really quite mild actions if I take my time, I get there eventually. If I can use a drill to screw it I will do it, but if I can't get the builders bit it is quite hard.

GP – My bigger problem is the rotator cuff, that is not related to the bicep. It is getting that hand movement round so my hand is flat that's

KJ – trying to get forearm position?

GP – yeah, that's more of a challenge for me but that's just being in a sling. My stiffness is from the sling rather than that

TB – I can do it now, it is weak but I can do it. I get pain but that is more the arthritis.

LJ – I have got stim down here, at the moment tells my hand to turn over so I am using that to build up this part of my arm.

That is what I am working on at the moment, so don't know if you use the stim machine to do that?

GP – I do a stim machine on my rotator cuff, the back there that's the one that I find is weak. I mean this one here isn't too bad, it is trying to come out.

KJ – the shoulder movement and forearm movement?

PA – yeah I have not had the stim used in the physio department, apart from Andre who has left now. When in rehab he put one on, but he was using it more to see how successful. Because if there is no nerve conduction it doesn't work, the muscle don't work. And he was just using it purely to diagnose people that were maybe saying they had worse injuries than they did or to see how successful it was to show that there was no muscle there, but it gave an electrical signal. I have never had them used by a physio to make my muscles work but just that's the only time I have used one, just to diagnose to tell him he said he used it as a trial to see if like the transfer is successful, as it sends an electrical current/message doesn't it?

GP – They didn't give you the needle ones there?

PA – I went to somewhere and had loads of that done at another hospital, 3 hours of being prodded with pins. They said it wouldn't hurt just might be uncomfortable, just stuck needles in you which sent a charge all over your body. For me, it was one in the thumb.

1.08

KJ – it sounds like there is quite a lot we can take from this as well in trying to get a bit more consistency in information that people get before their operation, just even the therapy afterward. So people have exposure to similar experiences. That has been useful for us today and I hope you would agree, but also it sounds like there are quite a lot of common themes as to going back to the question 'how would you describe changes in elbow movement'? And how will we measure that minimal difference; I think function and movement and on an individual basis are key factors. So is it a general agreement that measuring kilograms as such and strength isn't that meaningful but maybe the bio feedback is more meaningful as a measuring?

TB – it is definitely about functionality.

KJ – Does the functionality and trying to break that down in to what you need to get to reach that individual goal?

SB – Yeah, if you looked at us all now elbow movement following our surgery we are all 100% aren't we? Because we can do that so...

KJ – but 100% maybe different to different people?

SB – Yes but as in able to turn keys, clean yourself, things like that. It is those sorts of things that are a little bit more individual.

PA – Very much so, because that is just a physical movement and that's the first movement I got back and I could do this with my arm so I could do that great across the body. No use of the hand couldn't use the shoulder so yeah I had a bicep, what can I do with it? But that's what was comfortable and being able to move it. You got use of your hand and your shoulder, and that is the only thing you needed to get back then you have got to get a different kind of functionality. You are not going to be training everything else, depends level of injury but the important thing I think is to motivate people correctly at the start and give them some realistic expectations and motivate them. This guy I met on the ward is 5 years down the line and same injury. Wizard arm, his advice to me was go a 150% on the physio and do everything you can. He said I just moped around feeling sorry for myself after the first surgeries and nothing ever happened and he had no functionality at all. So that was really good advice, but you meet other people who just take the meds, lie in bed and give up on life.

KJ – So that motivation is different for each individual isn't it, but that is quite key?

TB – Certainly for me they 2 key things were patience and positive thought. Patience because it isn't like taking a headache tablet.

JT – The complete understanding of pain, I don't think I thought or had any concept of what the nerve pain was going to be like. Education what actually kind of symptoms I would get and where the pain would be, I think it would have been... otherwise you just go on YouTube and watch the surgery. If you really want to know, and I maybe should have asked more.

TB – I still get that now, if I stretch it is almost like having the stim machine plugged in. if I stretch my arm up I still feel the MCN, but it is now comforting rather than pain I just think it feels lovely I am really stretching my muscle and I can feel it now.

KJ – well hopefully that is a positive note to end on really, just having that further down the line. That is a nice way to sum up the session really.

TB – yeah, patience is needed. If only it was as easy as taking an ibuprofen to cure a headache, patience and keep positive. Its fine I'm alright.

KJ – Well thank you very much everybody, I hope everybody has got something from it as well and meeting everybody. You have had long journey to get here so really appreciate your time.

TB – are you riding a bike again?

GP – yeah I am riding a bike and TTing as well which puts a real strain on yourself. When you are positioned like that for an hour or so, that is when you really feel it. Staying in the exact same position for ages and ages and ages, but it's all good.

TB – I am sort of ok, tired when sometimes changing gear but I have got a winter hack bike which you have to push to change gear but my posh bike is quite easy to do, changing gear electronically.

3.

## COREQ form for the Phenomenologic analysis

### COREQ (Consolidated criteria for REporting Qualitative research) Checklist

A checklist of items that should be included in reports of qualitative research. You must report the page number in your manuscript where you consider each of the items listed in this checklist. If you have not included this information, either revise your manuscript accordingly before submitting or note N/A.

Topic	Item No.	Guide Questions/Description	Reported on Page No.
<b>Domain 1: Research team and reflexivity</b>			
<i>Personal characteristics</i>			
Interviewer/facilitator	1	Which author/s conducted the interview or focus group?	99
Credentials	2	What were the researcher's credentials? E.g. PhD, MD	100
Occupation	3	What was their occupation at the time of the study?	100
Gender	4	Was the researcher male or female?	100
Experience and training	5	What experience or training did the researcher have?	100
<i>Relationship with participants</i>			
Relationship established	6	Was a relationship established prior to study commencement?	99
Participant knowledge of the interviewer	7	What did the participants know about the researcher? e.g. personal goals, reasons for doing the research	99
Interviewer characteristics	8	What characteristics were reported about the inter viewer/facilitator? e.g. Bias, assumptions, reasons and interests in the research topic	100
<b>Domain 2: Study design</b>			
<i>Theoretical framework</i>			
Methodological orientation and Theory	9	What methodological orientation was stated to underpin the study? e.g. grounded theory, discourse analysis, ethnography, phenomenology, content analysis	95-96
<i>Participant selection</i>			
Sampling	10	How were participants selected? e.g. purposive, convenience, consecutive, snowball	97
Method of approach	11	How were participants approached? e.g. face-to-face, telephone, mail, email	97
Sample size	12	How many participants were in the study?	97
Non-participation	13	How many people refused to participate or dropped out? Reasons?	0
<i>Setting</i>			
Setting of data collection	14	Where was the data collected? e.g. home, clinic, workplace	99
Presence of non-participants	15	Was anyone else present besides the participants and researchers?	99
Description of sample	16	What are the important characteristics of the sample? e.g. demographic data, date	98
<i>Data collection</i>			
Interview guide	17	Were questions, prompts, guides provided by the authors? Was it pilot tested?	nil
Repeat interviews	18	Were repeat inter views carried out? If yes, how many?	nil
Audio/visual recording	19	Did the research use audio or visual recording to collect the data?	
Field notes	20	Were field notes made during and/or after the inter view or focus group?	99
Duration	21	What was the duration of the inter views or focus group?	99
Data saturation	22	Was data saturation discussed?	nil
Transcripts returned	23	Were transcripts returned to participants for comment and/or	nil

Topic	Item No.	Guide Questions/Description	Reported on Page No.
		correction?	
<b>Domain 3: analysis and findings</b>			
<i>Data analysis</i>			
Number of data coders	24	How many data coders coded the data?	100
Description of the coding tree	25	Did authors provide a description of the coding tree?	100
Derivation of themes	26	Were themes identified in advance or derived from the data?	100
Software	27	What software, if applicable, was used to manage the data?	nil
Participant checking	28	Did participants provide feedback on the findings?	nil
<i>Reporting</i>			
Quotations presented	29	Were participant quotations presented to illustrate the themes/findings? Was each quotation identified? e.g. participant number	nil
Data and findings consistent	30	Was there consistency between the data presented and the findings?	100
Clarity of major themes	31	Were major themes clearly presented in the findings?	104
Clarity of minor themes	32	Is there a description of diverse cases or discussion of minor themes?	104

Developed from: Tong A, Sainsbury P, Craig J. Consolidated criteria for reporting qualitative research (COREQ): a 32-item checklist for interviews and focus groups. *International Journal for Quality in Health Care*. 2007. Volume 19, Number 6: pp. 349 – 357

Once you have completed this checklist, please save a copy and upload it as part of your submission. DO NOT include this checklist as part of the main manuscript document. It must be uploaded as a separate file.

## DELPHI explicit statements

There is little guidance for researchers who wish to use the Delphi technique, even though aspects of its methodology can be interpreted in a variety of ways. Most published work has provided guidance based on authors' experiences, rather than empirical research or theoretical justification for the methodological decisions made. One systematic review describes a variety of consensus techniques used for designing clinical guidelines (Murphy et al. 1998). The explicit statement of their guidelines is included below

**Table 2.** Recommended checklist that should be reported in studies using the Delphi technique to determine which outcomes to measure in clinical trials or systematic reviews.

<b>Size and Composition of the Panel</b>
The total number of participants invited, and the number who completed the first round
Whether the following types of participants were involved in the study: clinicians (and whether they were eligible on the basis of treating patients with the condition of interest, or whether clinical trial involvement was an additional requirement), patients or their families, researchers, biostatisticians, representatives from the pharmaceutical industry, representatives from drug regulatory authorities, or other types of participants.
The proportion of each type of participant described above
How participants were identified/sampled
<b>Methodology of the Delphi Process</b>
Administration of questionnaires: postal, email, Internet, in person (e.g., at a clinic), or at a meeting
Information about outcomes, known to the facilitators before the study, which was provided to participants before the first round: e.g., if the Delphi process followed a review of outcomes measured in clinical trials, were the results of the review shared with participants? Alternatively, if some work had been conducted prior to the Delphi (e.g., workshop meeting, or focus groups amongst patients), were the results presented to the participants?
How outcomes were considered in the first questionnaire: were participants asked an open question i.e., no outcomes were initially listed, or were they asked to comment on a pre-specified list? If the latter, was the source of the list identified? Where possible, the questions asked to participants should be described in the methods, or made available to the reader, as supplementary information.
What was asked in subsequent rounds: where possible, the questions asked to participants should be described in the methods, or made available to the reader, as supplementary information
Feedback to participants after each round: if the results were not fed back, but only certain outcomes were carried forward to the next round (e.g., only those suggested by at least 10% were carried forward), this should be clearly described
Level of anonymity should be described: In order to be "fully anonymised", participants should not know the identities of the other individuals in the group, nor should they know the specific answers that any other individual gave. In studies that are "quasi-anonymised", the participants know the identities of some or all of the other individuals, but do not know how they individually responded to any of the questions in any round. In studies that are not anonymised, participants know the identity of some or all of the other individuals, and also know how some or all of them responded to any of the questions in any round.
If a pre-determined definition of consensus was used, this should be clearly described in the methods section of the study report
Were non-responders invited to subsequent rounds, or were they excluded from the rest of the study? Were additional people invited as the Delphi progressed?
<b>Results</b>
Number of participants invited to each round
Number who completed every round
Results for each outcome scored by participants in each round: a measure of group response, preferably with a measure of distribution. If these data cannot be included in the publication, even as a supplementary file, it should be made available on request.
Measure of group response for each outcome scored by participants in the final round
Distribution of response for each outcome scored by participants in the final round
A comprehensive list of all the outcomes that participants agreed should be included in the core set
doi:10.1371/journal.pmed.1000393.t002

**Table 5.9.** Recommended checklist that should be reported in studies using the Delphi technique to determine which outcomes to measure in clinical trials or systematic reviews. (Sinha et al. 2011)

## 5.8 Explicit statement of information (as per Table 5.9)

**Size and composition of the panel** – 9 International Consultant Surgeons working in peripheral nerve surgery from 5 differing countries (US, Canada, Sweden, Netherlands, Finland, Norway, Germany, India, Scotland and England)

The respondents were all Consultant (Attending) Surgeons they were selected via invitation from two international meetings of Surgeons working in the field of peripheral surgeons.

**Methodology of the Delphi process** – The questionnaire was delivered via Google forms on line assessment. The respondents had received a 5 minute talk covering the concept of the Delphi process and the intention of the study. The Experts were invited to answer from their own experience. The questionnaires are included as an appendix. Between first and second rounds the results of the first answers were sent to the group. There was complete anonymity with the responses. There was no predetermined definition of consensus used. There were no individuals added to the process – those who responded to the first questionnaire were invited to respond to the second.