RESPONSIVENESS OF THE ACTIVE WRIST JOINT POSITION SENSE TEST FOLLOWING DISTAL RADIUS FRACTURE INTERVENTION

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by
Christos Karagiannopoulos
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Examining Committee Members:

Michael R. Sitler, Kinesiology
Carole Tucker, Physical Therapy
Susan L. Michlovitz, McMaster University
Ryan Tierney, Kinesiology
Scott H. Kozin, Shriners Hospital for Children

By

Christos Karagiannopoulos

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ABSTRACT

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Major Advisor: Dr. Michael R. Sitler

The primary purpose of this study was to determine the responsiveness of the active wrist joint position sense (JPS) test to detect wrist sensori-motor status change at 8 and 12 weeks following distal radius fracture (DRF) treatment intervention. Responsiveness, defined as the instrument's ability to accurately detect change, was analyzed via distribution- and anchor-based statistical methods. Distribution-based analysis encompassed both group- (i.e., effect size [ES], standardized response mean [SRM]) and individual-based (i.e., minimum detectable change [MDC]) statistical indices. Anchor-based analysis was used to determine the minimal clinically important deficit (MCID) value by linking active wrist JPS test scores to Patient Global Impression of Change (PGIC) scale values.

The secondary purposes of the study were to: 1) compare the active wrist JPS test responsiveness as reflected by its MCID value between non-surgical and surgical DRF treatment interventions, 2) compare the active wrist JPS test responsiveness as reflected by its MCID value between participants with high- and low-pain levels, 3) compare the active wrist JPS test scores between participants with high- and low-pain levels, 4) assess the relationship between active wrist JPS test MCID value and function, and 5) determine the intra-tester reliability of the PGIC scale for assessing global health status change following DRF treatment intervention.

A prospective cohort study design was utilized. Thirty-three participants between 25 and 90 (mean 59.72) years of age following any non-surgical and surgical DRF treatment intervention were recruited. The active wrist JPS test was determined to be highly responsive based on group-based statistical indices (ES [8 weeks = 1.53, and 12 weeks = 2.36] and SRM [8 weeks = 1.57, and 12 weeks = 2.14]). Statistically significant MDC values were 4.28 and 4.94 deg at 8 and 12 weeks following treatment initiation, respectively. Clinically meaningful MCID values at 8 and 12 weeks were 5.00 and 7.09 deg, respectively. Responsiveness levels were not significantly different between the two treatment and

pain-level groups at 8 and 12 weeks post DRF treatment intervention. High-pain participants demonstrated significantly greater JPS deficits at both 8 and 12 weeks, and a significant association existed between active wrist JPS test MCID value and function. The PGIC scale intra-tester reliability was found to be high (ICC = 0.97). Based on this study’s findings, clinicians can use this highly responsive test with confidence to measure statistically and clinically meaningful conscious wrist sensori-motor function change following DRF treatment.

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PART 1

RESPONSIVENESS OF THE ACTIVE WRIST JOINT POSITION SENSE TEST FOLLOWING DISTAL RADIUS FRACTURE INTERVENTION

Introduction

Various known physical impairments and functional deficits exist within the initial 12 weeks following distal radius fracture (DRF) non-surgical and surgical interventions (Cooney, Dobyns & Linscheid, 1980; McKay, MacDermid, Roth, & Richards, 2001; MacDermid, Richards, & Roth 2001; Harris, MacDermid & Roth, 2005; Handoll, Madhok & Howe, 2006; Davis & Baratz, 2010; Leversedge & Srinivasan, 2012). This is a clinically important time period with up to 50% of patient-reported functional recovery occurring (MacDermid, et al., 2001; MacDermid, Roth & Richards, 2003), requiring appropriate clinical decisions for proper patient progression through supervised physical therapy and/or home exercise programs. During this period, physical impairment improvements of pain, joint stiffness, and deficits in active range of motion (ROM) and grip strength are correlated with functional improvement (MacDermid,

Donner, Richards, & Roth, 2002; Karnezis & Fragkiadakis, 2002; Tremayne, Taylor, McBurney & Baskus 2002; Harris et al.; Lucado, Li, Russell, Papadonikolakis & Ruch, 2008). The Patient-Rated Wrist Evaluation (PRWE) questionnaire is considered the gold standard for measuring pain and functional change in this patient population due to its high responsiveness (MacDermid, 1996; MacDermid, Richards, Donner, Bellany & Roth, 2000).

Sensori-motor impairment is another important deficit that has been identified during the initial 12 weeks following DRF treatment (Karagiannopoulos, Sitler, Michlovitz, & Tierney, 2013). The sensori-motor control system encompasses a continuum of centrally processed peripheral proprioceptive input (Proske & Gandevia, 2009) that induces conscious and unconscious efferent responses for optimal joint function (Riemann, Myers & Lephard, 2002; Riemann & Lephart, 2002a). Because sensori-motor impairment negatively impacts neuromuscular control, its deficit diminishes joint stability and function (Riemann & Lephart, 2002b; Gandevia, Smith, Crawford, Proske, & Taylor, 2006)

Limited research has been conducted on sensori-motor impairment following DRF. Joint position sense (JPS) is a particularly important component of sensori-motor control, which is primarily initiated by muscle and cutaneous afferent receptors (Myers & Lephart, 2000;

Gandevia et al., 2006; Smith, Crawford, Proske, Taylor & Gandevia, 2009; Hagert, 2010). JPS provides a conscious sense of joint control (Hagert), and the active wrist JPS test has been reported to be a clinically meaningful measure for determining conscious sensori-motor impairment following DRF (Karagiannopoulos et al., 2013). Higher active JPS impairment is associated with greater functional deficit following DRF, resulting in a high correlation with the PRWE questionnaire. The two primary advantages of this test consist of simple instrumentation via a goniometer (Hagert) and ease of application in today's busy clinical settings.

Pain is a clinically meaningful impairment following DRF (MacDermid et al., 2002; MacDermid et al., 2003; Karagiannopoulos et al., 2013) due to its influence on wrist sensori-motor control (Karagiannopoulos et al.) and function (Harris et al., 2005). Persistent input of nociceptive signals lead to morphological central nervous system changes (May, 2008). Altered dorsal horn function in the spinal cord and distortion of the injured body part representation at the primary somatosensory cortex (i.e., central neuroplasticity; Flor, Nikolajsen & Staehelin-Jensen, 2006; Price, Verne & Schwartz, 2006; Borsook, 2007, May) and thalamus (Anderson, O'Hara, Lawson, Treede & Lenz, 2006) have been identified. The resultant central maladaptive neuroplastic changes

interfere with integration and interpretation of the reflex sensori-motor pathways, leading to joint position sense deficits (Skinner, Barrack, Cook, & Haddad, 1984; Barrett, Cobb, & Bentley, 1991; Sharma & Pai, 1997; Baker, Bennell, Stillman, Cowan, & Crossley, 2002).

Pain is reported to significantly influence wrist sensori-motor function as higher pain scores have been linked to greater sensory deficit, lower motor output, and greater muscle fatigue 8 weeks following DRF (Karagiannopoulos et al., 2013). In addition, active wrist JPS has been found to be an important clinical indicator for hand and wrist sensori-motor function, which is strongly correlated with pain following DRF. The exact magnitude of pain influence on the active wrist JPS test and its psychometric properties for determining sensori-motor change (e.g., improvement) following DRF have yet to be determined.

Important clinical decisions on patient treatment progression following DRF interventions are dependent on clinically meaningful results derived from valid and reliable objective measures (MacDermid et al., 2000). Psychometric properties of the active wrist JPS test have been established for inter-rater reliability only, which has been determined to be high (intra-class correlation coefficient [ICC] = 0.85; Karagiannopoulos et al., 2013). Its responsiveness (Guyatt, Walter & Norman, 1987) as

reflected by group- (i.e., effect size [ES], standardized response mean [SRM]) and individual-based (i.e., minimum detectable change [MDC], minimum clinical important difference [MCID]) statistical indices as well as distribution- (i.e., ES, SRM, MDC) and anchor-based (i.e., MCID) methods has yet to be reported. The same is true for the possible influences of treatment intervention and pain level on active wrist JPS test responsiveness as well as its association with function following DRF intervention.

Statement of the Purpose

The primary purpose of this study was to determine the responsiveness of the active wrist JPS test to detect wrist sensori-motor change at 8 and 12 weeks following DRF treatment intervention. Secondary purposes of this study were to: 1) compare the active wrist JPS test responsiveness as reflected by its MCID value between non-surgical and surgical DRF treatment interventions, 2) compare the active wrist JPS test responsiveness as reflected by its MCID value between participants with high- and low-pain levels, 3) compare the active wrist JPS test scores between participants with high- and low-pain levels, 4) assess the relationship between active wrist JPS test MCID value and function, and 5) determine the intra-tester reliability of the Patient Global

Impression of Change (PGIC) Scale for assessing global health status change.

Study Aims and Hypotheses

Primary Aim

To determine the responsiveness of the active wrist JPS test as reflected by its group- (i.e., ES, SRM) and individual-based (i.e., MDC and MCID) statistical indices to detect wrist sensori-motor status change following DRF treatment intervention.

Hypotheses for primary aim.

1. Active wrist JPS test will demonstrate moderate to high (≥ .50) responsiveness levels based on its group-based statistical indices following DRF treatment intervention.

2. Statistically significant change in wrist sensori-motor status will be detected by the active wrist JPS test individual-based statistical indices, reflecting a clinically meaningful wrist sensori-motor change (i.e., MCID) at ≥ 6 points of health status change (i.e., PGIC Scale) following DRF treatment intervention.

Secondary Aim 1

To determine if a significant difference existed between non-surgical and surgical DRF treatment interventions on the active wrist JPS test responsiveness as reflected by its individual-based MCID statistical index.

Hypothesis for secondary aim 1.

No significant difference will exist in active wrist JPS test responsiveness as reflected by its individual-based MCID value between non-surgical and surgical DRF treatment interventions.

Secondary Aim 2

To determine if a significant difference existed between high- and low-pain level participants following DRF treatment intervention on the active wrist JPS test score and responsiveness as reflected by its individual-based MCID value.

Hypotheses for secondary aim 2.

1. High-pain participants will have significantly higher active wrist JPS test scores than the low-pain participants.

2. High-pain participants will have a significantly greater active wrist JPS test MCID value than the low-pain participants.

Secondary Aim 3

To assess the relationship between the active wrist JPS test MCID and function as measured via PRWE among participants following DRF treatment intervention.

Hypothesis for secondary aim 3.

Active wrist JPS test MCID and function will have a moderate negative correlation.

Secondary Aim 4

To determine the intra-tester reliability of the PGIC scale for assessing global health status change in participants following DRF treatment intervention.

Hypothesis for secondary aim 4.

The PGIC Scale will have high intra-tester reliability for assessing global health status change in participants following DRF treatment intervention.

Methods

Research Design

A prospective cohort study design was used to determine the active wrist JPS test responsiveness as reflected by its group- and individual-based statistical indices to detect wrist sensori-motor status change following non-surgical and surgical DRF treatment interventions. The independent variables were treatment group (non-surgical and surgical), pain level (high and low), and time (baseline at study induction as well as at 8 and 12 weeks following DRF treatment). The dependent variables consisted of active wrist JPS psychometric properties of group- (i.e., ES, SRM) and individual-based (i.e., MDC, MCID values) statistical indices of responsiveness as well as PGIC and PRWE composite scores. Potential covariates were age, gender, and hand dominance. Sample size for the study was based on the power analysis conceptual framework as presented by Cohen

(1988). Based on a one-tail .80 a priori power with a .05 alpha level and .80 (large) effect size, it was determined that a sample size of 40 was required for the study (10 participants per group).

Participants

A convenience sample of thirty-three participants over 18 years of age following any non-surgical and surgical DRF treatment was recruited during their first physical therapy visit at the ATI Physical Therapy Center located at the OrthopaediCare Clinic (Chalfont, PA). The study was approved by the Temple University Institutional Review Board. Each participant completed and signed approved informed consent (Appendix A) and Health Insurance Portability and Accountability Act (Appendix B) forms.

Participation was voluntary. Eligibility was determined based on the following inclusion criteria: attending surgeon (n = 7) approval to participate in the study; ability to speak, read, and write in English; 18 years of age or older; completion of a non-surgical or surgical DRF treatment intervention; provision of supervised physical therapy by a certified hand therapist; and ability to actively flex and extend the wrist a minimum of 10 and 30º, respectively.

Specific exclusion criteria applied to all potential participants of the study. The exclusion

criteria consisted of extended length of immobilization that did not permit testing at 8 weeks following fracture treatment, carpal tunnel syndrome or other neurological pathology resulting in paralysis or paresis of the involved arm, rheumatoid disease in the wrist or hand, cognitive impairment that prevented the patient from following instructions safely, concomitant ipsilateral extremity injury or fracture within the last 6 months or a concomitant ulna fracture as a result of the current DRF injury, ipsilateral upper extremity lymphedema that affected wrist and hand motion, blindness, pregnancy, and insurance coverage under workers compensation or no fault auto accident carrier.

Instrumentation

Data recording forms. Three investigator-generated data recording forms were used in the study: Participant Demographic and Characteristics (Appendix C), Participant Screener (Appendix D), and Data Collection (Appendix E). The Participant Demographic and Characteristics Form was used to collect information regarding each participant's age, gender, injury side, hand dominance, DRF treatment intervention, date of surgery, length of immobilization period, start date of physical therapy, number of weeks in therapy, and final post-treatment assessment date. The Participant Screener Form was used to obtain information regarding each participant's past and present medical

conditions, which was used to determine eligibility for participation in the study. This information was obtained via participant interview or was extracted from each participant's standard of care medical history record, which is typically obtained for all incoming patients at the ATI Physical Therapy Center. The Data Collection Form was used to record data for the active wrist JPS test.

Patient's Global Impression of Change Scale. The PGIC Scale (Appendix F) is a global disability rating scale, which is used as an external criterion instrument to determine clinically significant changes in treatment outcome (Jaeschke, Singer & Guyatt, 1989; Juniper, Guyatt, Willan & Griffith, 1994; Farrar, Young, LaMoreaux, Werth & Poole, 2001; Hurst & Bolton, 2004). In this study, the PGIC scale was anchored to the active wrist JPS test to determine its MCID value.

The PGIC Scale requires each participant to estimate his/her health-condition change by answering a single question, using a 7-point (1 to 7) numerical rating scale. Each number corresponds to descriptors that range from "no change or worse" (i.e., number 1) to "great deal better" (i.e., number 7; Schmitt & Di Fabio, 2004; Hurst & Bolton, 2004). In this study, the question was stated as follows: since the beginning of your initial fracture treatment (surgery or cast), how would you describe the change (if any) in activity

limitation, symptoms, emotions and overall quality of life, related to your painful wrist condition? This question is slightly modified from its original version as reported by Hurst and Bolton to improve its use in the current study. PGIC Scale cutoff scores of ≥ 6 have been reported to have high sensitivity, specificity and accuracy values (i.e., 74 to 83%) for identifying clinically significant change of health status with a moderate to high effect size (i.e., ≥ .06) among low back and neck pain patients (Hurst & Bolton). Strong validity (i.e., criterion, $p < 0.001$) and high test-retest reliability (ICC = .91) have been reported for the PGIC scale among male and female patients following distal upper extremity injuries including DRFs (Schmitt & Di Fabio). Data collected in this study were used to determine the psychometric properties of the proposed PGIC scale version among patients following their DRF intervention.

Patient-Rated Wrist Evaluation. The PRWE questionnaire (Appendix G) was used to determine each participant's pain level and wrist functional disability using an 11-point (0 to 10) scale. This questionnaire is comprised of 15 questions, which are grouped into 2 sub-scales: pain and function. The pain sub-scale consists of 5 items that measure pain under both resting and functional activity conditions. The

function sub-scale measures specific activities on 6 items and usual function on 4 items. Specific activity items assess dysfunction on functional tasks, such as turning a door knob, cutting with a knife, fastening buttons, pushing off a chair, carrying 10 pounds of weight, and using bathroom tissue. Usual activity items assess activities of daily living associated with everyday work, personal care, recreational, and household activities. (MacDermid, 1996)

Sub-scale and composite PRWE scores are obtained via the following methods. The pain sub-scale is scored by computing the sum of all its 5 items. The function sub-scale is scored by computing the sum of all its 10 items divided by 2. The final PRWE composite score is based on the sum of the final pain and function sub-scale scores out of 100, with higher scores indicating increasing perceived level of disability (MacDermid 1996). The PRWE composite score as well as each sub-scale independently have been determined to have high reliability among wrist-injured patients (ICC range 0.89 to 0.93), including DRF patients (MacDermid; MacDermid, Turgeon, Richards, Beadle & Roth, 1998). The PRWE has high validity (i.e., construct and criterion; $p < 0.0001$) and been determined to be highly responsive (SRM = 2.95) up to 6 months following DRF intervention (MacDermid et al., 2000).

Joint position sense assessment. Conscious proprioception was tested via a standardized active wrist JPS test (Karagiannopoulos et al., 2013). Active JPS is the ability to accurately reproduce a specific joint angle while vision is blocked (Hagert, 2010). During this test, each participant was asked to reproduce a predetermined wrist joint angle while having his/her eyes closed. Keeping the participant's eyes closed during the test is required (Myers & Lephart, 2000; Hagert) as proprioceptive input from visual afferent centers can play a complementary role on sensori-motor joint control (Riemann et al., 2002).

Joint angle was measured through use of a modified goniometric technique as described by LaStayo and Wheeler (1994). Each participant was seated facing a medical plinth. The involved elbow was positioned on the medical plinth in a flexed position with the forearm and wrist in a neutral position and fingers in a resting, flexed position. A standard goniometer (McCoy Health Science Supply, Maryland Heights, MO) with a central 360° scale marked in 2 deg increments and two 18 cm long arms was used. The goniometer was placed over the volar wrist with its moving arm aligned palmarly with the third metacarpal, stationary arm placed at the distal forearm, and axis adjacent to the wrist.

A standardized protocol was followed for active wrist JPS testing. The examiner showed each participant a reference wrist position by passively moving the wrist into 20° of extension with the goniometer placed volarly to the wrist (Appendix H). This test position was selected due to its biomechanical significance on conscious sensori-motor control (Werner et al., 1996). Peak wrist flexor-extensor tendon forces occur at ± 20° of wrist flexion-extension active ROM, promoting optimal joint stability during grasping activity. Each participant was asked to memorize this angle holding the position for 3 sec. The goniometer was then removed from the wrist, and the participant was asked to move his/her wrist into a fully flexed position prior to moving into wrist extension, reproducing the 20º angle. When a participant verbally confirmed that the target angle was attained, the examiner measured the final wrist active ROM. The difference between the referenced and actively reproduced wrist angles was used as the JPS deficit criterion value. The greater the angular difference the greater the JPS deficit. A zero value was assigned when exact reproduction of the referenced wrist extension angle was attained. Positive or negative values were assigned for angular differences greater or lesser to the referenced angle, but only the absolute values of the recorded angular differences were considered. The mean

value of two trials was used for data analysis. The intra-tester reliability of this test has been reported to be high (ICC = 0.85; Karagiannopoulos et al., 2013).

Procedures

Participant study induction occurred within 2 to 3 weeks following surgery or immediately following 4 to 6 weeks cast immobilization. The investigator discussed the purpose and procedures of the research study with each participant and conducted the consent process. Potential participants were provided unlimited time to review and ask questions about the informed consent form prior to signing it. If potential participants were uncertain about participating in this study, they were provided a blank copy of the informed consent to review at home for later consideration for participation in the study. Their course of treatment was unaltered.

Study induction procedures followed the following sequence. Upon expressing interest of participation in the study, each participant provided informed consent. The Participant Demographic and Characteristics and Participant Screener Forms were completed during the first physical therapy visit prior to study participation. Information from these two forms was used for determination of the inclusion and exclusion criteria. Those who met the inclusion criteria and were free of exclusionary factors were enrolled in the study.

At the first testing session, each participant was assigned to either the non-surgical or surgical treatment group based on his/her treatment intervention prior to study induction. Participants in each treatment group were further stratified into a high- or low-pain group, based on their PRWE baseline pain score. The sequence for participant group assignment is presented in Appendix I. The low pain group consisted of participants with PRWE pain subscale scores of < 35/50. The high pain group consisted of participants with PRWE pain subscale scores of ≥ 35/50. Pain impairment of ≥ 35/50 in the PRWE pain sub-scale has been linked to greater risk for developing chronic wrist and hand pain with long-term disability following DRF intervention (Mehta, 2013). Based on clinical experience, comparable treatment type and pain level groups sample sizes were anticipated.

The following order of testing was implemented in each testing session: PGIC Scale trial 1, PRWE, active wrist JPS test, and PGIC Scale trial 2. Each participant was tested at baseline (first 1 - 3 physical therapy visits upon meeting the inclusion criteria for wrist extension active ROM) as well as at 8 and 12 weeks following non-surgical and surgical intervention (Appendix J). This approach allowed for equalization of the total healing time-period, which started upon DRF intervention initiation (i.e., first day of cast or day

of surgery) and extended to 12 weeks following fracture intervention for both groups. The PGIC Scale was completed twice at baseline, the results of which were used to determine its intra-tester reliability. The time lapse between the two PGIC trials was approximately 20 min (i.e., total time required to complete all data collection). If a participant was discharged from physical therapy prior to 12 weeks following DRF intervention, he/she was asked to return for a final post-treatment assessment.

All data collection took place at the same clinic each participant received his/her physical therapy services. No physical therapy treatment was provided prior to completion of each testing session. All physical therapy treatments were provided by the primary investigator who is a licensed physical therapist and certified hand therapist with 15 years of clinical experience. Physical therapy treatments were standardized to follow the investigator’s usual care following non-surgical and surgical DRF interventions. Physical therapy interventions included home-care instruction, thermal modalities, active and passive ROM exercises, manual techniques, and strengthening methods as indicated.

Data Analysis

Data were analyzed using descriptive and inferential statistics. The primary aim hypothesis was analyzed via

both distribution- and anchor-based statistical methods (Appendix K-1). Distribution-based analysis encompassed both group- (i.e., ES, SRM) and individual-based (i.e., MDC) statistical indices that depended on estimating score variance and standard error of measurement (Lehman & Velozo, 2010) among the three assessment points in time (i.e., baseline as well as at 8 and 12 weeks following treatment intervention). ES was defined as the magnitude of the mean score change divided by the initial scores standard deviation (Portney & Watkins, 1993). SRM was defined as the mean score change divided by the standard deviation of the score change (Lehman & Velozo). Both ES and SRM were interpreted as follows: .20 to .49 small, .50 to .79 moderate, and ≥ .80 large effects (Portney & Watkins; Lehman & Velozo). MDC was defined as the smallest statistically significant detectable score change over time given the instrument of interest measurement error (Stratford et al., 1996; Schmitt & Di Fabio, 2004; Lehman & Velozo; De Morton, Davidson & Keating, 2010). MDC value was determined via the formula: $MDC = z * SEM * \sqrt{2}$, where SEM is the standard error of measurement. A z score of 1.96 was used to reflect a 95% confidence level (Lehman & Velozo).

An anchor-based analysis was used to determine the MCID value, which is an individual-based statistical index. In this analysis, individual active wrist JPS test

scores were linked to their corresponding PGIC scale values among the three assessment points in time (i.e., baseline, and 8 and 12 weeks). The mean change score for the active wrist JPS test, which corresponded with the PGIC scale criterion score that reflected clinically meaningful change (i.e., ≥ 6 points), was used as the final MCID value (Jaeschke et al., 1989; De Morton et al., 2010). MCID was defined as the smallest clinically significant score change (Jaeschke et al.; Juniper, 1998; Lehman & Velozo, 2010).

Secondary aims 1 and 2 hypotheses were analyzed using single-factor analysis of covariance (ANCOVA) to test the main effect of treatment group (non-surgical and surgical) and pain group (high and low level) on the MCID statistical index dependent variable, controlling for the effect of age, gender, and hand dominance. Secondary aim 2 hypothesis was analyzed with the independent t-test to determine if pain-level group differences existed on active wrist JPS test score.

Secondary aim 3 hypothesis was analyzed using Pearson's correlations to determine the relationship between active wrist JPS test MCID value and function (i.e., PRWE) among all participants following DRF interventions. Pearson correlation relationships were interpreted as follows: .25 to .50 fair, .51 to .75 moderate and values above .75 strong. Repeated measures

single-factor ANOVAs for active wrist JPS test MCID values and PRWE scores were also conducted to determine if statistical significance (e.g., clinical meaningfulness) existed for each main effect between 8 and 12 weeks (i.e., MCID) and among baseline, 8 weeks, and 12 weeks (i.e., PRWE) following DRF intervention. Dependent t-tests were used to determine if PRWE score differences existed between each time interval (i.e., baseline to 8 weeks, and 8 to 12 weeks). Clinical meaningfulness was determined by calculating the effect size (i.e., partial eta square), which reflected the amount of total variance accounted for one variable when the effect of the other variable was removed. Partial eta square was interpreted as follows: .01 - .05 small, .06 - .14 medium, and above .14 strong effect size (Huck, 2008).

Secondary aim 4 hypothesis was analyzed via ICC statistics (Model 3; Portney & Watkins, 1993) to determine the tester’s intra-rater reliability for the PGIC scale.

An overview of the data analysis plan for the study is presented in Appendix K. The Statistical Package for the Social Sciences, version 20.0 (SPSS, Chicago, IL) was used for all data analyses. Statistical significance was set at $p \leq .05$ for all

study aims. Bonferroni correction was completed for analyses involving multiple t-tests.

Results

Raw data for the non-surgical and surgical participants are presented separately in Appendix L. Descriptive and clinical characteristics for all study participants are presented in Tables 1 and 2. No significant difference existed between the surgical and non-surgical treatment groups for age (average 59.72 ± 11.9 years of age [range 25 – 90]). The majority of the participants were right-handed females who received surgical intervention via volar plating and reported low-pain levels upon study induction. Participants in the surgical treatment group had a significantly shorter immobilization period and longer physical therapy duration as compared to their non-surgical counterparts. High-pain participants required significantly longer physical therapy, reported significantly greater baseline functional disability, and had significantly greater JPS deficits at 8 and 12 weeks following DRF intervention than low-pain participants.

Descriptive statistics for all participants’ active wrist JPS test scores and score changes between baseline and 8 weeks as well as between baseline and 12 weeks following DRF treatment initiation are presented in Table 3. An overview of the study’s anchor-based data analysis,

Table 1. Participant Descriptive and Clinical Information

	Surg	Non-Surg	t	Sig
Participants (n = 33)	20	13		
Mean Age (SD)	58.4 (14.1)	61.6 (7.6)	-.754	.457
Gender				
Males (n = 5)	3	2		
Females (n = 28)	17	11		
Hand Dominance				
Right (n = 27)	18	9		
Left (n = 6)	2	4		
Treatment Type				
Volar Plating	16			
P. Pins	2			
Both	2			
Immob in Wks (SD)	3.3 (1.7)	5.1 (1.0)	-3.32	.002
Pain Level				
Low (n = 18)	10	8		
High (n = 15)	10	5		
Mean PT in Wks (SD)	7.5 (2.1)	5.5 (1.8)	2.78	.009
Mean PT Visits (SD)	13.6 (6.4)	8.9 (4.0)	2.34	.026

Note: Surg = Surgical Group, Non-Surg = Non-Surgical Group, t = T-Test, Sig = Statistical Significance at ≤ .05, SD = Standard Deviation, Wks = Weeks, PT = Physical Therapy, Immob = Immobilization Period, and P. Pins = Percutaneous Pinning.

Table 2. Pain-Level Group Participant Clinical Information

	Low Pain	High Pain	t	Sig
Mean PT Visits (SD)	9.8 (5.5)	14.0 (6.0)	-2.079	.046
Mean PRWE (SD)				
Baseline	47.6 (11.3)	74.5 (6.7)	-8.083	.000*
8 Wks	27.1 (12.5)	32.3 (13.1)	-1.166	.253
12 Wks	10.5 (10.5)	18.0 (13.4)	-1.785	.084
Mean JPS (SD)				
Baseline	10.2 (2.6)	11.6 (3.3)	-1.389	.175
8 Wks	5.3 (1.7)	7.4 (2.8)	-2.527	.016*
12 Wks	3.0 (1.3)	4.7 (2.3)	-2.622	.013*

Note: t = T-Test, Sig = Statistical Significance at ≤ .05, * = Statistical Significant with Bonferroni Correction (.05/3) = -0.167, SD = Standard Deviation, PT = Physical Therapy, PRWE = Patient Rated Wrist Evaluation, Wks = Weeks, and JPS = Joint Position sense.

which used each participant's PGIC outcome and active wrist JPS test change score at 8 and 12 weeks following DRF treatment initiation, is presented in Tables 4 and 5. Participants' PGIC outcome scores were stratified into two sub-groups (i.e., ≤ 5 and ≥ 6 points). Individual active wrist JPS change scores were linked to PGIC score sub-groups, which served as an external criterion. The active wrist JPS test score changes that were linked to the ≥ 6 PGIC score sub-group were clinically meaningful (i.e., MCID). A clinically meaningful wrist sensori-motor

Table 3. Active Wrist JPS Deficit and Deficit Change (Degrees) among Participant Groups at 8 and 12 Weeks Following DRF Treatment Intervention Initiation

	Baseline		8 Wks		Change 8 wks		12 Wks		Change 12 Wks	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Treatment										
Surg (n = 20)	10.85	3.00	5.75	2.04	5.10	3.21	3.65	1.72	7.30	3.45
Non-Surg (n = 13)	10.92	3.10	7.07	3.04	3.84	2.33	4.30	2.42	6.69	3.19
Pain Level										
Low (n = 18)	10.22	2.60	5.33	1.74	4.88	2.92	3.05	1.30	7.16	3.03
High (n = 15)	11.66	3.37	7.40	2.89	4.26	2.98	4.73	2.31	6.93	3.73
Collapsed (n = 33)	10.87	3.01	6.27	2.52	4.60	2.92	3.81	1.99	7.06	3.31

Note: JPS = Joint Position Sense, DRF = Distal Radius Fracture, Wks = Weeks, SD = Standard Deviation, Surg = Surgical Group, Non-Surg = Non-Surgical Group, Change 8 Wks = JPS deficit change between baseline and 8 weeks, and Change 12 wks = JPS deficit change between baseline and 12 weeks.

Table 4. PGIC Scale Scores and Active Wrist JPS Mean Change Scores (SD) between Baseline and 8 Weeks Following DRF Treatment Intervention Initiation

PGIC scale	No change 1	Almost the same 2	A little better 3	Somewhat better 4	Moderately better 5	Better 6	A great deal better 7
PGIC Scale Score Sub-Groups (Cases)			≤ 5 (n = 7)			≥ 6 (n = 26) (n = 19)	(n = 7)

	JPS Change						
Treatment	(N)	Mean	(Range)	(SD)	(N)	Mean	(Range)	(SD)
Surg (n = 20)	(5)	3.60	(2.0 – 7.0)	(2.30)	(15)	5.60	(0.0 – 13.0)	(3.37)
Non-Surg (n = 13)	(2)	2.00	(1.0 – 3.0)	(1.41)	(11)	4.18	(1.0 – 8.0)	(2.35)
Pain Level								
Low (n = 18)	(2)	3.00	(1.0 – 5.0)	(2.82)	(16)	5.12	(1.0 – 13.0)	(2.94)
High (n = 15)	(5)	3.20	(2.0 – 7.0)	(2.16)	(10)	4.80	(0.0 – 11.0)	(3.29)
Collapsed (n = 33)	(7)	3.14	(1.0 – 7.0)	(2.11)	(26)	5.00	(0.0 – 13.0)	(3.01)

Note: PGIC = Patient Global Impression Change Scale, JPS = Joint Position Sense, SD = Standard Deviation, Surg = Surgical Group, Non-Surg = Non-Surgical Group, and JPS Change = JPS mean change score between baseline and 8 weeks.

Table 5. PGIC Scale Scores and Active Wrist JPS Mean Change Scores (SD) between Baseline and 12 Weeks Following DRF Treatment Intervention Initiation

PGIC Scale	No change 1	Almost the same 2	A little better 3	Somewhat better 4	Moderately better 5	Better 6	A great deal better 7
PGIC Scale Score Sub-Groups (Cases)			≤ 5 (n = 0)			≥ 6 (n = 33) (n = 9)	(n = 24)

	JPS Change		
Treatment	Mean	(Range)	(SD)
Surg (n = 20)	7.30	(2.0 – 15.0)	(3.45)
Non-Surg (n = 13)	6.69	(3.0 – 15.0)	(3.19)
Pain Level			
Low (n = 18)	7.16	(3.0 – 15.0)	(3.03)
High (n = 15)	6.93	(2.0 – 15.0)	(3.73)
Collapsed (n = 33)	7.09	(2.0 – 15.0)	(3.31)

Note: PGIC = Patient Global Impression Change Scale, JPS = Joint Position Sense, SD = Standard Deviation, Surg = Surgical Group, Non-Surg = Non-Surgical Group, and JPS Change = JPS mean change score between baseline and 12 weeks.

change was detected in 26 (78%) and 33 (100%) participants at 8 and 12 weeks, respectively. The PGIC scale test-retest reliability was determined to be high (ICC = 0.97).

The responsiveness of the active wrist JPS test as reflected by its group- (i.e., ES, SRM) and individual-based (i.e., MDC and MCID) statistical indices to detect wrist sensori-motor status change at 8 and 12 weeks following DRF treatment initiation are presented in Table 6. Results demonstrated high (≥ .80) responsiveness based on the ES and SRM statistical indices for both treatment groups and both pain levels at 8 and 12 weeks. Instrument MDC values were consistently lower than MCID values for both treatment and pain-level groups.

Treatment and pain-level group differences for the MCID values at 8 and 12 weeks following DRF treatment intervention were assessed via ANCOVAs. No significant differences were detected for the main effect for treatment group and potential covariates at 8 weeks [$F(1, 21) = 1.560$, $p = .230$] and 12 weeks [$F(1, 28) = .182$, $p = .673$]. Similarly, no significant differences were detected for the main effect for pain level and potential covariates at 8 weeks [$F(1, 21) = .007$, $p = .934$] and 12 weeks [$F(1, 28) = .009$, $p = .926$]. The high pain-level group had significantly ($p < .0167$) higher active wrist JPS test scores than the low pain-

Table 6. Active Wrist JPS Test Responsiveness Statistical Indices as Reflected by Group- and Individual-Based Statistical Indices Following DRF Treatment Intervention Initiation

Participant Group	ES	SRM	MDC	MCID
8 Weeks				
Treatment				
Surg (n = 20)	1.69	1.58	4.49	5.60
Non-Surg (n = 13)	1.22	1.64	3.42	4.18
Pain Level				
Low (n = 18)	1.87	1.69	4.22	5.12
High (n = 15)	1.26	1.42	4.28	4.80
Collapsed (n = 33)	1.53	1.57	4.28	5.00
12 Weeks				
Treatment				
Surg (n = 20)	2.42	2.11	4.90	7.35
Non-Surg (n = 13)	2.13	2.09	4.75	6.69
Pain Level				
Low (n = 18)	2.75	2.36	3.89	7.16
High (n = 15)	2.05	1.85	5.39	6.93
Collapsed (n = 33)	2.36	2.14	4.94	7.09

Note: JPS = Joint Position Sense test, DRF = Distal Radius Fracture, ES = Effect Size, SRM = Standardized Response Mean, MDC = Minimal Detectable Change, MCID = Minimal Clinically Important Difference, Surg = Surgical Group, and Non-Surg = Non-Surgical Group.

level group at 8 and 12 weeks following DRF treatment interventions. All ANCOVAs tables are presented in Appendices M-1 through M-4.

Pearson correlations between active wrist JPS test MCID value and function (i.e., PRWE) for all study participants at 8- and 12-weeks following DRF treatment intervention are presented in Table 7. A significant fair negative and a non-significant poor negative correlation were detected between MCID and PRWE values at 8 and 12 weeks, respectively. These results were contrasted by repeated measures single-factor ANOVAs, which determined statistically significant main effects with strong effect sizes for both active wrist JPS test MCID values (i.e., between 8 and 12 weeks) and PRWE scores (i.e., among baseline, 8 weeks, and 12 weeks) following DRF treatment intervention (Appendix N-1).

Table 7. Pearson Correlations for Function and MCID Responsiveness Value among all Participants at 8 and 12 Weeks Following DRF Treatment Intervention Initiation

Variables	MCID at 8 Weeks	MCID at 12 Weeks
PRWE 8	-.349*	
PRWE 12		-.074

Note: JPS = Joint Position Sense, MCID = Minimal Clinically Important Difference, PRWE = Patient Rated Wrist Evaluation, DRF = Distal Radius Fracture, and * = statistically significant at ≤ .05.

A statistically significant change in PRWE scores was observed between baseline, 8 weeks, and 12 weeks for all participants following DRF treatment intervention (Table 8). Dependent t-test analysis with a Bonferroni correction (.05/2 = .025) determined that mean PRWE scores significantly decreased between baseline and 8 weeks (t[32] = 11.010, p = .000) as well as between 8 and 12 weeks (t[32] = 11.613, p = .000) for all participants.

Table 8. Mean PRWE Scores (SD) for All Participants at Baseline, 8 Weeks, and 12 Weeks Following DRF Treatment Intervention Initiation

PRWE	Baseline	8 Weeks	12 Weeks
Score (%)	59.84 (16.4)	29.51 (12.8)	13.92 (12.3)

Note: PRWE = Patient rated Wrist Evaluation, and SD = Standard Deviation.

Discussion

This is the first study to determine the active wrist JPS test responsiveness as reflected by its group- (i.e., ES, SRM) and individual-based (i.e., MDC and MCID) statistical indices following DRF surgical and non-surgical interventions among low- and high-pain level participants. The active wrist JPS test was determined to have high responsiveness at 8 and 12 weeks regardless of treatment group or pain level. A steady improvement of the active wrist JPS impairment occurred during the

initial 12 weeks following DRF intervention among all participants while high-pain participants demonstrated significantly greater JPS deficits at both 8 and 12 weeks following DRF intervention.

Responsiveness of an assessment outcome instrument refers to its ability to accurately detect change (e.g., sensori-motor function) that has occurred within its specific clinical domain (Guyatt et al., 1987; Wright & Young, 1998; Beaton, Bombardier, Katz & Wright, 2001; Lehman & Velozo, 2010) and is important for the delivery of effective clinical practice. In this study, the ES (8 weeks = 1.53, and 12 weeks = 2.36) and SRM (8 weeks = 1.57, and 12 weeks = 2.14) statistical indices indicated high levels of responsiveness for the active wrist JPS test for measuring sensori-motor change among both low- and high-pain level patients. Instrument MDC values were 4.28 and 4.94 deg at 8 and 12 weeks following treatment initiation, respectively. Thus, these changes should be considered statistically significant improvements at 8 and 12 weeks following DRF treatment intervention.

The study’s approach to determine the active wrist JPS responsiveness via distribution-based statistics (i.e., ES, SRM, MDC) is consistent with current research standards (MacDermid et al., 2000; Beaton, Katz, Fossel, Wright & Tarasuk, 2001; Schmitt & Di Fabio, 2004). The advantage of determining an instrument’s responsiveness

via the MDC value is twofold. First, it reflects the SEM associated with an individual's repeated score on a given instrument (Stratford et al., 1996). Second, it reflects the instrument's reliability (i.e., SEM) since the reliability coefficient (i.e., ICC) directly influences an instrument's SEM level (i.e., SEM = SD x √ 1-ICC) and, therefore, its MDC score (Schmitt & Di Fabio).

Determination of the MCID value via anchor-based statistics is also consistent with current clinical trends (Juniper et al., 1994; Hurst & Bolton, 2004; Schmitt & Di Fabio, 2004) and is important for determining an instrument's clinically meaningful changes over time. The advantage of this approach over other distribution-based statistical approaches (i.e., ES and SRM) is its ability to detect changes (e.g., sensori-motor wrist function change) from the patient's perspective (Hurst & Bolton; Lehman & Velozo, 2010). Active wrist JPS changes of 5.00 and 7.09 deg are clinically meaningful sensori-motor improvements at 8 and 12 weeks following DRF treatment intervention.

MCID values are influenced by various patient factors (e.g., education, socioeconomic status, depression, age) as well as baseline injury severity, introducing the potential for much greater score variability than the one that exists for the MDC. Accordingly, greater MCID instrument outcome change needs

to occur for a patient to perceive it as meaningful. An instrument is expected to have different MCID values for different patient populations (Cook, 2008).

The finding of no significant difference in MCID values regardless of treatment group was expected. Previous research has found no active wrist JPS deficit difference between surgical and non-surgical patients following DRF treatment interventions (Karagiannopoulos et al., 2013). A significantly greater MCID value among the high- than low-pain level participants was expected. It was assumed that higher-pain levels would lead to greater active wrist JPS deficits, necessitating a higher degree of JPS change (i.e., MCID) to reach clinical meaningfulness. Indeed, the high-pain participants had significantly greater JPS deficit than their low-pain counterparts at both 8 and 12 weeks following treatment initiation. However, the degree of JPS deficit change was comparable for both pain-level groups, indicating this test's responsiveness stability under both low- and high-pain conditions. It is yet to be determined if the inability to reach statistical significance for treatment type, pain level, and other covariates (i.e., hand dominance, age, gender) is due to the study's low statistical power.

The study's finding that the active wrist JPS test MDC values were lower than its MCID values for all

participant groups is also consistent with current literature findings (Beaton, Katz, et al., 2001; Schmitt & Di Fabio, 2004). A reliable instrument is expected to have a lower MDC than MCID value (King, 2011). The MDC value represents the smallest observed outcome change that exceeds the boundaries of an instrument's SEM (Lehman & Valozo, 2010; King). It also reflects an instrument's reliability. Both SEM and reliability are instrument-based variables. Thus, more reliable instruments are expected to be more responsive as they present lower SEMs and lower MDC values. The MDC value would not exceed the MCID value unless the instrument has poor reliability and responsiveness (Schmitt & DiFabio; King 2011).

A significant positive association existed between pain level and JPS deficit at both 8 (r = .413) and 12 weeks (r = .426) following DRF intervention. High-pain levels participants had greater wrist sensori-motor control deficit than low-pain participants. Similar findings have been reported by Karagiannopoulos et al. (2013) who determined a significant moderate (r = .627) association between JPS deficit and pain status at 8 weeks following DRF intervention.

Peripheral tissue injury and pain can result in central nervous system maladaptive changes (Merzenich et al., 1983; Knecht et al., 1996; Elbert et al.,1997; May,

2008) that interfere with proper integration and interpretation of reflex sensori-motor pathways (Borsook, 2007), leading to joint control deficits (Wand et al., 2011). A relationship between central neuroplasticity and loss of joint sensori-motor control has been determined among low back (Hodges & Richardson, 1999; Hodges & Richardson, 2003) and knee (Barrack, Skinner, Cook & Haddad, 1983; Sharma & Pai, 1997; Cowan, Bennell, Hodges, Crossley & McConnell, 2001; Baker et al., 2002) patient populations. This is the first study to provide evidence for an association between wrist conscious sensori-motor control loss and high-pain status during the initial 12 weeks following DRF intervention.

The significant association between active wrist JPS test MCID value and function (i.e., composite PRWE questionnaire score) was expected as significantly higher functional deficits have been associated with greater active wrist JPS deficits following DRF treatment interventions (Karagiannopoulos et al., 2013). Despite an observable strong negative association between the active wrist JPS test MCID and PRWE mean values during the initial 12 weeks period, Pearson correlation analysis indicated only a fair association at 8 weeks and a poor association at 12 weeks for the aforementioned variables. This was thought to be a result of low statistical power and score variance.

In contrast, based on the ANOVA analysis, statistically significant changes for both active wrist JPS test MCID values and PRWE scores existed following DRF treatment intervention: MCID significantly increased between 8 weeks and 12 weeks, and PRWE scores significantly decreased among baseline, 8 weeks, and 12 weeks. These results offer preliminary evidence that a clinically meaningful association may exist between MCID and PRWE scores, suggesting that a greater active wrist JPS MCID is required for measuring meaningful wrist sensori-motor change among patients who demonstrate greater improvement in functional status over time. This is important because establishing an association between function and active wrist JPS test responsiveness is required to validate the test's clinical value for identifying clinically meaningful wrist sensori-motor control deficit change following DRF treatment intervention.

The PGIC scale in this study served as an external criterion to determine the participants perceived level of global health change. A clinically meaningful wrist sensori-motor change was detected in 26 (78%) and 33 (100%) participants at 8 and 12 weeks, respectively. This was accomplished by linking the active wrist JPS test change scores to PGIC Scale scores of ≥ 6 for each participant at 8 and 12 weeks following DRF treatment

intervention. PGIC scale scores of ≥ 6 have been determined to offer optimal sensitivity, specificity and accuracy values (i.e., 74 to 83%) for identifying clinically significant change of health status with a moderate to high effect size (i.e., ≥ .06) among low back and neck pain patients (Hurst & Bolton, 2004).

Strong psychometric properties of the PGIC scale have already been established to support its clinical use. Schmitt and Di Fabio (2004) determined this scale's strong validity (i.e., criterion, $p < 0.001$) and high test-retest reliability (ICC = .91) among patients with distal upper extremity trauma. The current study demonstrated that this scale has high intra-rater reliability (ICC = 0.97) for DRF patients.

The strengths of the study included its design, methodology, and statistical approach. The prospective cohort design strengthened the internal validity in determining statistically significant active wrist JPS test responsiveness values as reflected by its group- (i.e., ES, SRM) and individual-based (i.e., MDC and MCID) indices. Use of a single-tester assessment approach prevented the potential for inter-rater errors during measurements. A single-clinician approach resulted in treatment standardization as clinical reasoning and rehabilitation methodology remained consistent for all study participants.

In addition, the inclusion of SRM and anchor-based statistics strengthened the study's results. SRM is considered a superior statistical coefficient for instrument responsiveness because it is not affected by sample size (Stratford, Binkley & Riddle, 1996). Furthermore, anchor-based analysis allowed for determining the active wrist JPS test MCID value, which is considered the instrument's most meaningful patient-based responsiveness index in clinical practice (Hurst & Bolton, 2004; Lehman & Velozo, 2010).

The findings of this study must be interpreted, however, within the content of several methodological limitations. A small sample size was an apparent study weakness, which could have mitigated finding significant group differences. Low statistical power could have also contributed to the non-significant findings for the covariates' (i.e., hand dominance, age and gender) cofounding effects on study outcomes. In addition, although injury healing time was equalized for both treatment groups (i.e., 12 weeks from treatment initiation), immobilization time and physical therapy duration were not. The surgical group had a significantly shorter immobilization and longer physical therapy time than the non-surgical group. This could have advantaged the surgical participants, perhaps having a positive effect on their sensori-motor outcomes. Equalizing

treatment groups for physical therapy duration was unattainable due to the physicians' protocol differences (i.e., immobilization duration and patient study entry-point) following DRF intervention. Although treatment type was adequately standardized, group differences were likely to exist based on initial fracture severity and surgeon experience level. The use of a non-blinded tester was another limitation for the study's internal validity, introducing the possibility for rater bias. Finally, the single-clinician, single-research site approach posed a threat to the study's external validity. The study results should be generalized with caution to other geographical regions due to differences in post-fracture treatment protocol, referral to physical therapy, and/or rehabilitation regiment practices.

Decisions on Hypothesis

Primary Aim

1. The active wrist JPS test demonstrated high (≥ .50) responsiveness based on its group-based statistical indices following DRF treatment intervention. Primary aim 1 hypothesis was accepted.

2. Statistically significant change in wrist sensori-motor status was detected by the active wrist JPS test individual-based statistical indices, reflecting a clinically meaningful wrist sensori-motor change (i.e., MCID) at ≥ 6 points of health status change on the PGIC

scale following DRF treatment intervention. Primary aim 2 hypothesis was accepted.

Secondary Aim 1

No significant difference existed between the treatment groups in active wrist JPS test responsiveness as reflected by its MCID value. Failed to reject secondary aim 1 hypothesis.

Secondary Aim 2

1. High-pain group participants did not have significantly higher active wrist JPS test responsiveness as reflected by its MCID value in comparison to their low-pain group counterparts. Failed to accept secondary aim 2 hypothesis 1.

2. High-pain group participants had significantly higher active wrist JPS test scores in comparison to their low-pain group counterparts. Secondary aim 2 hypothesis 2 was accepted.

Secondary Aim 3

A significant moderate negative correlation was not demonstrated between the active wrist JPS test MCID and function as measured via the PRWE among participants following DRF treatment intervention. Failed to accept secondary aim 3 hypothesis.

Secondary Aim 4

The PGIC Scale demonstrated high intra-tester reliability for assessing global health status change in

participants following DRF treatment intervention. Secondary aim 4 hypothesis was accepted.

Conclusion

The findings of the study indicated that the active wrist JPS test is a highly responsive instrument for measuring conscious wrist sensori-motor control deficit at 8 and 12 weeks following DRF treatment intervention, regardless if treated non-surgically or surgically and of pain level. During this critical healing time, significantly greater wrist sensori-motor control impairment existed among DRF patients who experienced higher levels of pain. This finding implies an association between incoming nociceptive signals and central neuro-plastic cortical changes that may lead to sensori-motor control impairment following DRF. Based on the study's findings, clinicians can use this highly responsive test with confidence to measure statistically and clinically meaningful conscious wrist sensori-motor function change following DRF treatment.

Recommendations for Future Research

1. Research studies with larger sample sizes are needed to determine whether pain has an effect on the active wrist JPS test responsiveness as well as validate an association between the active wrist JPS test MCID value and function following DRF treatment intervention.

2. Whether clinical variables such as injury severity, bone density, and psycho-social factors (e.g., depression and anxiety) have an effect on the psychometric properties of the active wrist JPS test following DRF treatment is yet to be determined. Further research is needed to explore this possibility.

3. It is important as we explore more about the influence of pain on the central nervous system to better understand if pain following DRF leads to neuroplasticity, resulting in decreased active wrist joint control and function. As research in this area is in its infancy, further work is needed to explore the explicit neuro-muscular patho-physiology for altered wrist proprioception following DRF.

4. Treatment of wrist sensori-motor impairment following DRF needs to be advanced based on evidence-based practice principles. Current knowledge on active wrist JPS test psychometric properties should be used in future prospective clinical trials for the purpose of determining treatment efficacy following DRF interventions.

5. Further research is needed to determine the most clinically meaningful contributing factors (e.g., natural body healing, treatment effect, compliance with home program) to the observed wrist sensori-motor impairment

improvement during the initial 12 weeks following DRF treatment.

PART 2

REVIEW OF LITERATURE

Forearm and Wrist Joint Anatomy

Skeletal

The skeleton of the forearm region is formed by the radius and ulna bones. The cylindrical shaped proximal radial head has a concave end that articulates with the capitulum of the distal humerus. The proximal ulna is much larger than its distal end and is formed by the olecranon process and its concave trochlear notch that articulates with the convex trochlea of the distal humerus (An, Morrey & Chao, 1984). The larger radius distal end is formed by its rectangular shaped epiphysis that projects distally via the radial styloid process at its lateral border (Eathorne, 2005). The mildly convex dorsal aspect of the distal radius forms the Lister tubercle as well as other osseous prominences that enhance extensor tendon stability and serves as a fulcrum for extensor tendon function (Simic & Weiland, 2003). The distal cylindrical shaped ulnar head is also projected distally via its ulnar styloid process (Eathorne).

Joint

The forearm region consists of three articulations: proximal, middle, and distal radioulnar joints (Graham, Fisher, Hotchkiss, & Kleinman, 1998; Werner & An, 1994). The proximal radioulnar joint is supported by the annular and quadrate ligaments (Sojbjerg, Ovesen & Gundorf, 1987). The annular ligament surrounds the radial head and attaches to the anterior and posterior edges of the radial notch. The quadrate ligament connects the neck of the radius to the base of the radial notch (Regan, Korinek, Morrey & An, 1991).

At the middle radioulnar articulation, the interosseous membrane connects the radius with the ulnar via its obliquely oriented fibers (Hotchkiss, An, Sowa, Basta & Weiland, 1989). The oblique cord is a proximal thickening of the interosseous membrane that has twice the thickness of the adjacent membrane. Its fibers are obliquely oriented at about 90° to the rest of the membrane (Graham et al., 1998; Hotchkiss et al.).

At the distal radioulnar joint, the convex ulnar head articulates with the concave ulnar notch of the distal radius. This joint is reinforced by its own capsule as well as posterior and anterior radioulnar ligaments (Berger, 1996; Glowacki, Koch, Weiss, & Akelman, 1997). The distal radioulnar joint capsule is

separate from the radiocarpal joint capsule and consists of inferior, volar, and dorsal aspects (Graham et al., 1998). The inferior aspect of the distal radioulnar joint capsule starts at the distal medial articular surface of the radius and blends with the triangular fibrocartilage disc that extends medially and attaches to the ulnar styloid process, triquetrum, and ulnar collateral ligament. The triangular fibrocartilage disc separates the distal radioulnar and radiocarpal joints (Vezeridis, Yoshioka, Han & Blazar, 2010). This triangular fibrocartilagenous complex is continuous with the posterior and anterior radioulnar ligaments, providing primary support at the inferior aspect of the distal radioulnar joint (Nikolaidis, Hildreth, & Lichtman, 2000; Brown, Fliszar, Cotton, truddell, & Resnick, 1998). Although all three aspects of the distal radioulnar joint capsule are anatomically continuous, its inferior aspect is much thicker, compared to its volar and dorsal aspects (Kleinman & Graham, 1998).

The radiocarpal joint is formed between the biconcave articular surfaces of the distal radius and triangular fibrocartilage disc, proximally, and the convex articular surfaces of the scaphoid and lunate carpal bones, distally. Its capsule attaches to the proximal carpal bones, triangular fibrocartilage disc, and distal articular surface of the radius, forming a single

uninterrupted articular cavity (Berger, 1996). The articulation between the proximal and distal carpal rows forms the midcarpal joint. The proximal carpal row consists of the scaphoid, lunate, and triquetrum bones. The distal carpal row consists of the trapezium, trapezoid, capitate, and hamate bones. The midcarpal joint articular orientation is biconcave medially and single plane laterally (Berger; Kijima & Viegas, 2009). Although the articular surfaces of the midcarpal joint lack continuity, continuous capsules interconnect all of the underlying intercarpal articulations (Cardoso & Szabo, 2007).

Both the radiocarpal and midcarpal joints are supported by volar, dorsal, and collateral extrinsic ligaments (Berger, 1996; Cardoso & Szabo, 2007). The dorsal radiocarpal ligaments connect the radius to the lunate and triquetrum via the dorsal radiotriquetral and intercarpal ligaments (Viegas, Yamaguchi, Boyd & Patterson, 1999). The volar radiocarpal capsule consists of three intracapsular components: radioscaphocapitate, radiolunotriquetral, and short radiolunate ligaments. The volar ulnocarpal capsule consists of two separate intracapsular components: ulnolunate and ulnotriquetral ligaments (Kijima & Viegas, 2009; Yasumu & Viegas, 2009). The ulnar collateral ligament connects the ulnar styloid process with the triangular fibrocartilage disc as well

as pisiform and triquetrun carpal bones (Brown et al., 1998). The radial collateral ligament connects the distal radius to the scaphoid, trapezium, and first metacarpal bones (Kijima & Viegas). Additional support of the distal carpal row is derived via the common dorsal and volar carpometacarpal ligaments that interconnect the distal carpal row with each base of the second through fifth metacarpal bones at the carpometacarpal joints (Treumann et al., 2002). These carpometacarpal ligaments, along with the interosseus metacarpal ligaments, reinforce the capsule of each carpometacarpal joint, which is virtually immobile (Kijima & Viegas; Berger).

Inter-carpal stability depends on intrinsic ligaments that interconnect adjacent carpal bones at both the proximal and distal carpal rows. These include the scapholunate, lunotriquetral, triquetrohammate, volar and dorsal scaphotrapeziotrapezoid, and deltoid ligaments (Berger, 1996, Kijima & Viegas, 2009; Yasumu & Viegas, 2009). The deltoid ligament consists of two components, triquetrocapitate and scaphocapitate, which form a V-shaped configuration (Viegas et al, 1999). The triquetroscaphoid ligament provides additional intrinsic support along the same plane as the deltoid ligament at the volar wrist (Brown et al., 1998; Yasumu & Viegas).

Muscle

The forearm consists of two separate compartments: anterior and posterior. The musculature in the anterior forearm compartment forms superficial and deep layers (Ronel, Mtui & Nolan, 2004). The superficial layer muscles originate from the medial epicondyle of the humerus via the common flexor tendon (Eathorne, 2005) and consist of the pronator teres; palmaris longus; flexor carpi radialis and flexor carpi ulnaris (Desai, Shuler & Seiler, 2012). The flexor digitorum superficialis muscle is located within the superficial anterior forearm compartment (Ronel et al.) and its fibers originate from the medial epicondyle of the humerus, proximal ulna, and mid-shaft of the radius (Lieber, Jacobson, Fazeli, Abrams & Botte, 1992). The entire superficial anterior compartment musculature except the pronator teres and palmaris longus cross the anterior aspect of the wrist (Ronel et al.) and insert either into the ventral base of the second metacarpal, pisiform, or middle phalanx base of the second through fifth digits (Lieber et al.). The pronator teres has two heads that converge inferiorly and laterally to insert into the mid-portion of the radius (Steinberg & Plancher, 1995). The palmaris longus, if present, is in the anterior mid-forearm and inserts into the palmar aponeurosis of the wrist (Pratt, 1991).

The deep anterior compartment muscles originate from the ventral aspect of the radius, interosseous membrane, and ulna (Lieber et al., 1992). They consist of the pronator quadratus, flexor pollicis longus, and flexor digitorum profundus. The pronator quadratus is a rectangular-shaped muscle that interconnects the anterior distal ulna and radius (Desai et al., 2012). The flexor pollicis longus and flexor digitorum profundus cross the anterior wrist and insert at the base of the distal phalanx of the second through fifth digits as well as base of the distal phalanx of the thumb (Steinberg & Plancher, 1995).

The musculature of the posterior forearm compartment forms superficial and deep layers as well (Desai et al., 2012). The posterior compartment superficial layer muscles originate from the distal shaft as well as lateral epicondyle of the humerus (An, Hui, Morrey, Lincheid & Chao, 1981). They consist of the brachioradialis, extensor carpi radialis longus and brevis, extensor digitorum, extensor digiti minimi, and extensor carpi ulnaris muscles (Ronel et al., 2004). With the exception of the brachioradialis muscle, all of the superficial layer muscle tendons originate at the common extensor tendon, pass under the extensor retinaculum at the dorsal-lateral wrist, and insert separately or collectively into the base of the second and third

metacarpal, second through fifth digits extensor aponeurosis at the metacarpalphalangeal joints, and base of fifth metacarpal (Eathorne, 2005). The brachioradialis, which is the most superficial muscle in the posterior forearm compartment, originates at the lateral supracondylar ridge of the distal humerus and inserts at the distal lateral radius (Koh, Andersen, Buford, Patterson & Viegas, 2006).

The posterior compartment deep layer muscles originate from the lateral epicondyle, dorsal aspect of the radius, interosseous membrane, and ulna (Eathorne, 2005). They consist of the supinator, abductor pollicis longus, extensor pollicis brevis and longus, and extensor indicis muscles (Ronel et al., 2004). With the exception of the supinator, which fibers extend distally and attach around the proximal radius, all other deep muscles descend through the dorsal-lateral wrist and insert separately or collectively at the ventral base of the first metacarpal, bases of the proximal and distal phalanges of the thumb, or second digit extensor metacarpalphalangeal joint aponeurosis (Steinberg & Plancher, 1995).

Nerve

Neural innervation of the forearm and wrist regions is provided by the median, ulnar, and radial nerves (Eathorne, 2005). The median nerve enters the anterior

forearm through the cubital fossa, passes between the two heads of the pronator teres, and descends deep to the flexor digitorum superficialis where it branches into the anterior interosseous nerve. At the wrist, the median nerve is located between the palmaris longus and flexor carpi radialis tendons, and it enters the hand through the carpal tunnel. The median nerve innervates all the superficial muscles of the anterior compartment except for the flexor carpi ulnaris. The anterior interosseous nerve supplies all of the deep muscles of the anterior compartment except for the portion of the flexor digitorum profundus that controls the fourth and fifth digits. The median nerve provides cutaneous innervations at the lateral-ventral forearm; palmar aspects of the thumb, index, middle fingers and lateral half of the ring finger; and their associated areas at the central and proximal palm (Ronel et al., 2004). A branch of the anterior interosseous nerve innervates the volar capsule of the wrist (Berger, 1996; Brown et al., 1998).

The ulnar nerve enters the forearm through the cubital tunnel, passes between the two origins of the flexor carpi ulnaris muscle, and descends deep to that muscle throughout the medial forearm. At the wrist, it emerges under the flexor carpi ulnaris tendon, passes superficial to the deep flexor retinaculum, and enters the hand through Gyuon’s canal. The ulnar nerve supplies

the flexor carpi ulnaris, the remaining ulnar half of the flexor digitorum profundus, and all intrinsic muscles of the hand. The ulnar nerve provides cutaneous innervations at the medial-ventral forearm and ulnar hand, including the fifth and medial half of the fourth digits. (Eathorne, 2005)

The radial nerve enters the forearm via passing between the brachialis and brachioradialis muscles and then splits into a deep and superficial branch. The deep branch first inervates the brachioradialis, extensor carpi radialis longus and bravis, extensor digitorum, extensor digiti minimi, extensor carpi ulnaris, and supinator muscles. It then branches into the posterior interosseous nerve, innervating all of the remaining deep muscles of the posterior forearm compartment (Steinberg & Plancher, 1995). The superficial branch of the radial nerve descends under the brachioradialis muscle, emerging at the distal third of lateral forearm to provide cutaneous innervations at the dorsal-lateral wrist; hand; and thumb, second, third, and lateral half of fourth fingers (Eathorne, 2005).

Forearm and Wrist Joint Biomechanics

The biomechanics of the forearm joint resemble a “bucket and handle” mechanical system where the bow-shaped radius rotates around a relatively fixed and straight ulna in a single axis (Graham et al., 1998).

The forearm joint axis of rotation originates at the fovea, which is the margin between the distal ulnar articular surface and ulnar styloid process (Werner & An, 1994). It passes through the interosseous membrane and intersects the center of the radial head at the proximal radioulnar joint (Linscheid, 1986). The unique osteological relationship between the radius and relatively straight-shaped ulna allows for maximum ROM with minimum bony contact during forearm pronation and supination (Graham et al.). The radius crosses the ulna in full pronation and is parallel to the ulna in full supination. Full pronation is limited by both ligamentous tension and bony approximation when the radius contacts the ulna, and full supination is limited only by passive ligamentous tension (Berger, 1996).

Ligamentous passive tension throughout the forearm joint primarily controls pronation and supination end ROMs (Graham et al., 1998), with normal values estimated to be 85 to 90° (American Academy of Orthopedic Surgeons, 1965). At the proximal radioulnar joint, the annular ligament confines the radial head within the ulnar radial notch, allowing the radial head to spin on the capitulum of the humerus during pronation and supination (Graham et al.). Radial head spin is controlled by the quadrate ligament for both pronation and supination end ROMs (Hotchkiss et al., 1989). The oblique cord, along with

the rest of the interosseous membrane, functions to transmit and absorb forces exerted along the forearm as well as to control diastatic tension forces between the radius and ulna (Graham et al.; McGinley & Kozin, 2001).

At the distal radioulnar joint, pronation and supination are the product of arthrokinematic motions of slide and roll within the radial notch (Jaffe, Chidgey, & LaStayo, 1996; Werner & An, 1994). These accessory motions are controlled by the dorsal and ventral radioulnar ligaments and triangular fibrocartilagenous disc (Graham et al., 1998). In supination, the ulna translates volarly and proximally relative to the distal radius, resulting in an ulnar-minus position. In pronation, the ulna translates dorsally and distally relative to the distal radius, resulting in an ulnar–plus position (Glowacki et al., 1997). Tension of the posterior radioulnar ligament controls anterior ulnar translation during supination and ulnar rotation during pronation. Conversely, tension of the anterior radioulnar ligament controls posterior ulnar translation during pronation and ulnar rotation during supination (Jaffe et al.; Werner & An). Tension at the anterior and posterior aspects of the triangular fibrocartilagenous complex control supination and pronation motions only at their end ranges (Linscheid, 1986; Werner & An). Other supporting structures of the distal radioulnar joint

during pronation and supination include the ulnar notch and interosseous membrane. These structures provide passive stabilization, while the pronator quadratus and extensor carpi ulnaris tendon provide dynamic stabilization to the distal radioulnar joint (Glowacki et al.; Nikolaidis et al., 2000).

Total forearm pronation and supination ROMs are the result of combined motions occurring within a multilinked articulation system of the forearm and wrist joints (Flowers, Stephens-Chisar, LaStayo, & Galante, 2001). Throughout this mechanical unit, compression and tensile forces directed from bony and ligamentous structures dictate both the quality and quantity of pronation and supination end ROMs (Vezeridis et al., 2010). During pronation and supination, ligamentus tension maintains the carpus parallel to the forearm, allowing only 10° of rotation at the radiocarpal joint (Linscheid, 1986). A combination of radiocarpal and intercarpal rotation contributes an additional 40° to total available pronation and supination ROMs (Flowers et al.).

The radiocarpal and mid-carpal joints form a biaxial ellipsoid wrist complex in which flexion-extension and radial-ulnar deviation motions are generated around coronal and sagital axes, respectively (Werner & Plancher, 1998). As the convex surface of the carpal

bones articulates with the concave surface of the distal radius and triangular fibrocartilagenous disc, the proximal carpal row glides volarly in extension and dorsaly in flexion. The same concave-convex rule applies at the mid-carpal joint where the distal carpal row glides radialy in ulnar deviation and ulnarly in radial deviation (Berger, 1996). Normal wrist active ROM in flexion is 80 to 90°, in extension is 70 to 90°, in radial deviation is 15°, and ulnar deviation is 30 to 45° (American Academy of Orthopedic Surgeons, 1965). Each of the radiocarpal and mid-carpal joints contribute approximately 50% in the total amount of wrist flexion and extension ROMs (Werner & Plancher).

The distal aspect of the radius is an integral osseous structure for wrist stability and axial force transmission. Its wide metaphysial end is divided into lateral, intermediate, and medial osseous columns. The lateral column serves as an important base for wrist ligament attachment. The intermediate column functions as a primary center for load transmission. The medial column primarily controls forearm rotation and assists in axial load distribution (Chen & Jupiter, 2007). The distal radius and ulna are responsible for transmitting 80 and 20% of the axial loading forces at the wrist, respectively (Berger, 1996). The obliquely oriented distal radius articular surface is characterized by its

11° volar tilt and 22° radial inclination (Cardoso & Szabo, 2007). This distinct oblique articular orientation of the distal radius results in greater force dispersion of the radiocarpal joint during axial loading (Berger).

Wrist motion is dependent on both active and passive mechanisms to control the alignment of the distal radius with the radiocarpal, midcarpal, and distal radioulnar articulations (Simic & Weiland, 2003). Wrist extension is primarily controlled via the extensor carpi radialis longus and brevis and extensor carpi ulnaris muscles (Riek & Bawa, 1992). Wrist flexion is primarily controlled via the flexor carpi ulnaris and radialis muscles (Jones, Bawa & McMillan, 1993). Synergistic action of the extensor carpi radialis longus and brevis and flexor carpi radialis muscles moves the wrist in radial deviation. Ulnar deviation is primarily controlled by the concurrent contraction of the extensor and flexor carpi ulnaris muscles (Bawa, Chalmers, Jones, Sogaard & Walsh, 2000).

Passive tension of both intrinsic and extrinsic ligaments of the wrist accompanies muscle function for the completion of all wrist physiological motions (Berger, 1996). During both wrist flexion and extension, the proximal carpal row functions as an intercalated segment between the radius and distal carpal row. There are no direct muscle attachments at the proximal carpal

row. The distal carpal row is stabilized by both passive ligamentous forces and active forces exerted by the extrinsic forearm muscles (Linscheid, 1986). Compression and tensile forces on the proximal carpal row during wrist flexion and extension are controlled primarily by ligamentous tension of the palmar and dorsal radiocarpal ligaments and scaphoid bone, which is considered to be a connective bridge between the proximal and distal carpal rows. Terminal wrist flexion and extension ROMs are limited by the cumulative compression and tensile forces exerted by all interacting articulations and their intrinsic and extrinsic supporting ligaments within the wrist complex. Similar forces, mediated by the biconcave midcarpal articular surfaces, collateral, and intrinsic intercarpal ligaments, restrain terminal wrist ulnar and radial deviation motions. Additional ligamentous tension from the ulnocarpal and intercarpal ligaments contributes further to wrist stability and enables the hand to follow wrist motion with minimal lag (Berger).

Wrist Sensori-Motor Control

Overview

Maintaining functional joint stability depends on both static and dynamic components, which are intermediated by intact sensori-motor pathways (Myers & Lephart, 2002). The sensorimotor system, which is a

complex integral constituent of the motor control system in humans, encompasses all of the sensory, motor, and central integration and processing components involved with maintaining joint homeostasis during functional bodily movement (Riemann & Lephart, 2002b; Solomonow & Krogsgaard, 2001). Historically, proprioception has been erroneously used as a synonymous term with sensorimotor control (Riemann & Lephart, 2000a). Sensorimotor system, which was established in 1997 by the Foundation of Sports Medicine Education and Research group experts, is currently considered to be a more relevant term than proprioception (Lephart & Fu, 2000; Riemann & Lephart, 2002a).

Proprioception and sensorimotor control are two fundamentally different functions. Proprioception is defined as only the afferent information deriving from peripheral mechanoreceptors, whose primary function is to contribute towards joint stability and postural control (Sherington, 1906). In contrast, the sensorimotor system encompasses incoming afferent proprioceptive information from a variety of peripheral and joint sources (Proske & Gandevia, 2009), their central integration, and resulting conscious or unconscious efferent neuromuscular responses towards joint stability and postural control (Riemann & Lephart, 2002a). Incoming afferent proprioceptive signals are conveyed to the cerebral cortex and cerebellum via

ascending spinal cord and brain stem pathways for central integration and interpretation (Brooke, 2004; Solomonow & Krogsgaard, 2001).

Central afferent signal processing regulates efferent reactive proactive feedforward or feedback mechanisms for conscious or unconscious joint neuromuscular control (Riemann and Lephart, 2002a; Simoneau et al., 1999). A feedforward mechanism is a pre-learned anticipatory reaction, and its activation precedes a sensory stimulus (Hagert, 2010; Proske et al., 2000; Simoneau et al.). Feedback control refers to the corrective motor response after the reception and central processing of a sensory stimulus (Hagert; Riemann and Lephart, 2002b). Body kinesis results in constant incoming proprioceptive signals that provide essential information for corrective feedback needed for motor planning modifications as well as proper updating of the feedforward command system (Riemann and Lephart; Sjolander, Johansson, & Djupsjobacka, 2002).

Components of Sensori-Motor System

The three main structural components of the sensorimotor control system are the somatosensory receptors, peripheral afferent and efferent nervous system pathways, and central nervous system processes (Gilman, 2002; Lephart & Fu, 2000). Somatosensory receptors that are specialized to sense and convey

proprioceptive signals from a joint are called mechanoreceptors and are located within static (i.e., joint capsule, ligaments, skin) and dynamic (i.e., tendon, muscle) afferent sources (Hagert, Garcia-Elias, Forsgren, & Ljung, 2007). Mechanoreceptors are specialized sensory organs that are activated as a result of mechanical deformation (i.e., joint pressure, motion, velocity) applied to their host membrane, transmitting neural signals proportional to the degree of their deformation (Proske, 2006). They are connected to class I and II large diameter myelinated nerve fibers with conduction velocities of 75 to 120 and 30 to 75 m/sec, respectively (Gilman). Class I consists of A-alpha (Aα) large-diameter nerve fibers that offer the fastest conduction velocities. They encompass the Ia and Ib fibers, which are involved in the function of the muscle spindle, golgi tendon organs (Metso, Palmu, & Partanen, 2008), and rapidly responding articular and cutaneous mechanoreceptors (Gilman). Class II consists of A-beta (Aβ) medium-diameter nerve fibers that offer slower conduction velocity than class I. They mainly consist of cutaneous and joint mechanoreceptors with a slower response to an applied afferent stimulus (Gilman; Metso, Paimu & Partanen, 2008).

Mechanoreceptors that mediate tactile and vibration sensations are the Meissner corpuscles, Merkel discs,

Ruffini endings, and Pacinian corpuscle. Meissner corpuscles and Merkel discs are located within the superficial skin. Meissner corpuscles are rapid-adapting receptors that respond only to the initial mechanical stimulus, which is imposed cutaneously. Merkel discs are slow-adapting receptors and respond to constant cutaneous stimulus of touch, pressure, and vibration (Gilman, 2002). Ruffini endings and Pacinian corpuscles are located in deeper subcutaneous and joint tissues. Ruffini is a slow-adapting, low-threshold neuroreceptor, which is constantly detecting tissue stretch, axial ligament loading, and tensile strain forces (Gilman; Hagert, 2010), which are important to joint position and motion (Hagert et al., 2007). The Pacinian corpuscle is a rapid-adapting, low-threshold receptor capable of detecting sudden joint acceleration and deceleration as well as joint compressive forces (Hagert). The golgi-like ending receptors resemble the ruffini ending morphology and are classified as spray endings. They are rapid-adapting, high-threshold neuroreceptors, which are responsible for detecting tensile ligamentous strain when joint movement reaches extreme ROM ranges (Hagert; Lephart & Fu, 2000). Other unclassifiable corpuscles as well as fascicular type free nerve endings that have been identified in the vicinity of joint ligaments and capsule may also further

transmit joint proprioceptive feedback (Hagert, Forsgren, & Ljung, 2005; Lephart & Fu).

The muscle spindle and golgi tendon organ are mechanoreceptors that provide dynamic proprioceptive feedback for joint stability (Proskie, 2006; Riemann & Lephart, 2002a). The muscle spindle is an encapsulated sensory organ that contains its own intrafusal fibers and is located within the mid portion of a muscle in alignment with the extrafusal fibers (Proske, Wise & Gregory, 2000). Contraction of the intrafusal fibers is controlled by gamma motor neurons and results in an increase of its firing rate as well as elevation of its sensitivity to any given extrafusal muscle fiber length change (Proskie et al.; Konishi, Kasukawa, Tobita, Nishino, & Konishi, 2007). The main function of the muscle spindle is to sense and convey afferent signals deriving from changes in both the quantity and rate of extrafusal muscle fiber length (Riemann & Lephart; Konishi et al.).

When the alpha-motor neuron is activated and a consequent muscle contraction is induced, the intrafusal muscle spindle fibers are momentarily unloaded and their sensitivity to extrafusal muscle fiber tension is lessened. The reduced fiber tension results in alpha and gamma-motor neurons activation and a concurrent facilitation of intrafusal and extrafusal muscle fiber

contraction (Proske et al., 2000). This mechanism helps to maintain steady intrafusal fiber tension levels and constant ability of the Ia and II afferent fibers to detect extrafusal fiber length change during muscle contraction (Riemann & Lephart, 2002a). Independent gamma-motor system activation is also necessary to optimize muscle spindle intrafusal fiber readiness at extreme muscle length ranges where the muscle spindle effectiveness becomes limited. Gamma-motor activity regulates the tension of the intrafusal fibers and restores constant baseline receptor sensitivity throughout the muscle contractile range (Riemann & Lephart, 2002b). This important role of the gamma-motor system in voluntary motor activity is highlighted by the fact that nearly 31% of all motor nerve fibers of a muscle are gamma-efferent fibers (Guyton, 1991). Co-activation of the gamma and alpha-motor mechanisms produces constant Ia and II muscle spindle afferent fiber signals that are transmitted to the spinal cord for maintaining proper muscle tone, regulating myotatic spinal reflexes, and facilitating supraspinal motor responses appropriate for joint control (Proske et al.; Riemann & Lephart, 2002a).

The golgi tendon organ is an encapsulated type of mechanoreceptor and is housed within the musculotendinous segment of a muscle in a series arrangement (Jami, 1992;

Riemann & Lephart, 2002a). Each golgi tendon organ is linked to 10 to 50 muscle fibers (Jami). Its main function is to constantly detect and respond to both static and dynamic changes in extrafusal muscle fiber tension throughout all muscle segments (Jami; Riemann & Lephart). Its function serves as a protective mechanism against excessive injurious muscle tension forces (Proskie et al., 2000). Afferent signals from golgi tendon organs are transmitted to the spinal cord via polysynaptic pathways of the Ib neuron as well as other supra-spinal centers (Jami).

Proprioceptive somatosensory signals from cutaneous receptors, joint mechanoreceptors, muscle spindles and golgi tendon organs are transmitted to the cerebral cortex and cerebellum via ascending pathways in the spinal cord and brain stem (Brooke, 2004; Solomonow & Krogsgaard, 2001). The main ascending pathway for these somatosensory senses is the dorsal column system within the dorsolateral funiculus (Gilman, 2002; Wall, 1960). This is a rapid-conducting pathway via large-diameter myelenated neurons that are orderly organized to represent segmental body regions. The first-order unipolar neuron of this somatosensory pathway is housed in the dorsal root ganglia. Axons from the first-order neuron enter the ipsilateral dorsal column and ascend via the gracile and cuneate tracts to the level of the caudal

medulla, where they synapse with the second-order neuron. Axons of second-order neurons cross the midline and form the medial lemniscus tract, which ascend through the pons and midbrain and terminate at the contralateral thalamus. Third-order neurons convey the sensorimotor signals further into higher interpretation centers located within the primary somatosensory cortex (Gilman).

The cerebral cortex is responsible for organizing and planning central motor commands (Braun et al., 2001). It initiates intricate and discrete voluntary movement patterns via encoding specific muscle activation sequencing to control production of muscle force and direction of movement (Braun et al.; Riemann & Lephart, 2002a). The cerebellum lacks the capacity to independently initiate motor commands. The cerebellum function is constantly regulated by the influx of incoming descending cortical and ascending peripheral information to subconsciously regulate motor planning and execution of complex, rapid, and precise motor tasks (Riemann & Lephart). Feedforward mechanisms are also activated by the cerebellum for accurately predicting the sensorimotor consequences of body movement. Such mechanisms monitor discrepancies between the predicted sensorimotor output and the actual feedback information received during motor actions, leading to proper

neuromuscular corrective responses (Blakemore, Frith, & Wolpert, 2001).

Sensorimotor System Integration

The sensorimotor control system encompasses both unconscious and conscious pathways (Hagert, 2010; Riemann & Lephart, 2002a). The unconscious pathway incorporates proprioceptive afferent signals mainly from joint receptors (Hagert, 2010; Johansson, Sjolander, & Sojka, 1991; Sjolander et al., 2002) that ascend the spinal cord via the spinocerebellar tract and are processed at the cerebellum, which is the primary center for reflex regulations needed during anticipatory joint control (Riemann & Lephart). The unconscious proprioceptive sense is linked to the feedforward anticipatory control of muscles around a joint and its primary function is to automatically maintain joint stability and equilibrium through neuromuscular control (Hagert, 2010; Myers & Lephart, 2000; Myers & Lephart, 2002).

Proprioceptive signals that ascend further and reach processing centers in the cerebral cortex contribute to the conscious sensorimotor pathway (Riemann & Lephart, 2002a; Hagert, 2010), regulating the senses of kinesthesia and joint position (Proske & Gandevia, 2009; Riemann & Lephart). Kinesthesia is defined as the human sense responsible for joint or limb motion perception (Hagert; Proske & Gandevia). This sense is primarily

controlled via proprioceptive feedback, deriving from muscle spindles (Proske, 2006; Proske et al., 2000) and, to a lesser extent, from skin receptors (Proske & Gandevia). The muscle spindle can signal limb movement throughout the ROM while skin receptors tend to respond mostly towards the end range of joint motion (Riemann & Lephart). Skin receptors play a primary kinesthetic role when joint movement is dependent on muscles not positioned directly over the joint but originating from anatomical areas adjacent to the joint (Hagert). Skin receptors at the wrist and hand play a primary kinesthetic role as the mobility of these anatomical regions depends on extrinsic muscles located at the forearm (Collins, Refshauge, Todd, & Gandevia, 2005). Vibration or tensile deformation of tendons crossing the wrist and hand joints further enhances kinesthetic sense during functional motion. Tendon vibration influences joint motion perception via muscle spindle activation (Cordo, Gurfinkel, Brumagne, & Flore-Voera, 2005; White & Proske, 2009).

JPS is defined as the sense required to consciously reproduce a joint angle with precision (Hagert, 2010; Proske & Gandevia, 2009). When body segment functioning occurs against gravity, JPS is primarily influenced by combined muscle spindle proprioceptive afferent information and alpha-motor efferent muscle commands

(Gandevia, Smith, Crawford, Proske, & Taylor, 2006; Smith, Crawford, Proske, Taylor, & Gandevia, 2009). The alpha-motor efferent command or “outflow” signal (Candevia et al., 2006) provides an additional afferent joint position cue. This is an elicited sensation of the required muscle effort to stabilize a body segment when loaded against gravity. Conversely, under unloaded limb conditions, where body positioning occurs passively in gravity assisted horizontal directions, alpha-motor sensory cues are minimized and JPS relies primarily on signals from muscle spindles (Ansems, Allen, & Proske, 2006; Winter, Allenm, & Proske, 2005). Joint capsule receptors (e.g., ruffini corpuscles) and skin receptors appear to influence JPS mostly at the end range of joint motion (Riemann & Lephart, 2002a). Muscle fatigue is another influential factor to JPS (Allen, Ansems, & Proske, 2007). Allen and Proske (2006) reported statistically significant JPS errors of 14.4 and 11.6º degrees in active elbow flexion and extension motions, respectively, as a result of elbow flexor and extensor muscle fatigue.

Afferent signals from both ligaments and muscles are transmitted to the dorsal horn of the spinal cord for continuous unconscious and conscious joint control, respectively. Such proprioceptive afferent information obtained during both static and dynamic postures induce

reflex feedback spinal and supraspinal mechanisms (Brooke, 2004; Myers & Lephart, 2002). These reflexes consist of either monosynaptic or polysynaptic pathways and activate corresponding muscles via an alpha-motor neuron connection (Riemann & Lephart, 2002a). Such reflexes may influence both agonist and antagonist muscle activity via reciprocal or recurrent inhibition (Hagert, 2010). Reciprocal inhibition utilizes spinal interneurons for concurrent facilitation and inhibition of agonist and antagonist muscle, respectively, to facilitate smooth joint movement. Recurrent inhibition uses collateral interneuron connections of the alpha-motor neurons with Renshaw cells to inhibit synergistic muscle activity and promote the action of antagonist muscles during transitional joint movement (Sharman, Cresswell, & Riek, 2006).

The direct ligament-muscle proprioceptive inter-connection towards joint control and stability was first demonstrated by Palmer (1958) at the knee joint and it was attributed to a monosynaptic medial collateral ligament reflex. Such a reflex mechanism was also reported later in the elbow and forearm (Phillips et al., 1997) and other major joints such as the shoulder (Guanche, Knatt, Solomonow, Lu, Baratta, 1995; Knatt, Guanche, Solomonow, 1995) and spine (Solomonow, Zhou, Harris, Lu, Baratta, 1998; Stubbs et al., 1998). All of

the aforementioned studies were conducted in animals (i.e., cats and sheep) and reported the presence of a ligament-muscle reflex with a latency of 2.5 to 5.0 ms. Such a quick-acting proprioceptive response is claimed to be a result of a monosynaptic spinal reflex pathway to maintain joint stability when a sudden ligamentus tension is elicited (Solomonow, 2006).

Research on the monosynaptic ligament-muscle proprioceptive reflex mechanism has been controversial when studied in humans. Proof for its existence, which was thought to protect a joint when the integrity of a ligament is threatened by harmful tensile forces, is limited due to conflicting evidence (Sjolander et al., 2002). Several studies have supported the existence of a short monosynaptic spinal reflex pathway that occurs with a 20 ms latency as a protective joint mechanism in the human spine (Solomonow et al., 1998) in the human knee (Solomonow et al., 1987) and, recently, in the human wrist (Hagert et al., 2007).

The aforementioned findings were refuted by an earlier study by Voigt, Jakobsen, and Sinkjaer (1998) who studied the ligament-muscle proprioceptive interconnection in the human shoulder via electrical stimulation of the anterior glenohumeral joint capsule. Such stimulus was found to elicit a significant inhibitory effect on the rotator cuff muscles with an

average latency of 33 ms and duration of 76 ms. This study's results failed to justify a ligament-muscle joint stabilization mechanism mediated by a monosynaptic reflex. Conversely, the muscle inhibitory effect was attributed to possible polysynaptic neuropathways mediated via slow-conducting Ib interneurons or inhibitory Ia afferent fibers to the rotator cuff muscles alpha-motor neurons.

Despite its publicity, the underlying physiological mechanism of the ligament-muscle reflex mechanism has not been clearly determined, and its relevance to joint motor control via quick-acting monosynaptic spinal reflex pathways has been debated among neuroscientists (Lephart & Fu, 2000). Most of the studies that supported its existence elicited such a proprioceptive reflex response via electrical stimulation applied on articular sensory receptors to evoke a muscle motor response (Grillner, Hongo, Lund, 1969; Johansson, Sjolander, Sojka, 1986; Scott, Ferrell, Baxendale, 1994). Such methodology is limited in that electrical stimulation does not truly reprecent a natural mechanical stimulus that would occur to human joints during functional activity (Lephart & Fu).

Instead, the results of several research studies support the presence of an alternative proprioceptive mechanism of a muscle gamma-motor system pre-activation

that involves articular afferents influencing joint motor control via the activation of the muscle spindle system (Lephart & Fu, 2000). In this proprioceptive mechanism, various afferent signals (e.g., skin, joint, muscle) offer an integrated proprioceptive input that influences the gamma-motor system activity via both central and supra-spinal center facilitation (Sjolander et al., 2002). In essence, the gamma efferent mechanism is pre-activated by the same proprioceptive input that excites the alpha-motor neurons. It also receives facilitatory input from the cerebellum, brain stem, and cerebral cortex (Riemann & Lephard, 2002b).

The gamma-motor system pre-activation mechanism has been convincingly supported by results of newer laboratory studies. These studies have indicated that ligament proprioceptive signals may contribute to joint stability and muscle coordination through polysynaptic ascending pathways and spinal reflex modulation mechanisms that ultimately participate in the pre-programming of the gamma-motor spindle system (Lephart & Fu, 2000; Sjolander et al., 2002). In these studies, the validity of the gamma-motor reflex mechanism was determined via mechanical loading methods that represent naturally occuring mechanical stimulus to human joints during functional activity. Mechanical tension forces of 5 to 40 N were applied to joint ligaments, and fusimotor

muscle reactivity was measured via electromyography (Johansson, Sjolander, Sojka, Wadell, 1989; Sjolander, Djupsjobacka, Johansson, Sojka, Lorentzon, 1994; Sojka, Johansson, Sjolander, Lorentzon, Djupsjobacka, 1989; Sojka, Sjolander, Johansson, & Djupsjobacka, 1991).

In essence, the latency associated with reflexive contraction from the alpha-motor neuron stimulation (i.e., time interval between application of a perturbing joint force and myoelectric event) may be too long to provide immediate joint stability alone (Myers & Lephart, 2002). A direct ligament-muscle reflex feedback mechanism would be too slow to provide joint protection alone as the latency in responding to an unanticipated stimulus can range from .15 to .30 ms, depending on the stimulus type (i.e., kinesthetic, visual, or auditory; Lephart & Fu, 2000). Activation of the gamma efferent system seems to be the most comprehensive and rapidly excitable mechanism that maintains high muscle contractile readiness, shortens the aforementioned latencies, and contributes to joint stability (Sjolander et al., 2002). In addition, conscious and unconscious muscle anticipatory reactions to external stimulus contribute to joint stability. These feed-forward processes are based on pre-learned motor experiences that are constantly modulated via incoming afferent feedback input to further reduce muscle reaction latency (Lephart & Fu).

Current evidence supports that dynamic joint stability primarily depends on the integration of proprioceptive feedback and feedforward mechanisms for the coactivation of alpha- and gamma-motor neurons (Hagert, Ljung, & Forsgren, 2004; Myers & Lephart, 2002; Sjolander et al., 2002). The feedback system is associated with monosynaptic and polysynaptic reflex pathways responsible for excitatory or inhibitory muscle activity around a joint (Proske, 2006). Thus, reactive excitation of alpha-motor fibers is accompanied by co-activation of gamma motor fibers, resulting in heightening of muscle spindle intrafusal fibers alertness and stiffness (Myers & Lephart; Riemann & Lephard, 2002b; Sojka et al., 1991). Pre-activation offers improved dynamic joint control as the latency between perception of a perturbing force and myoelectric event is shortened. Pre-activation of the muscle spindle also leads to shorter electro-mechanical delay between onset of muscle electrical activity and muscle force production (Granata, Ikeda, & Adel, 2000).

Concurrent feedforward neuromuscular control, which utilizes previous feedback experiences for motor planning and execution, produces preparatory muscle activity that enhances joint dynamic control via stiffening of the tenomuscular unit (Simoneau et al., 1999). This muscle preparatory mechanism also utilizes the gamma-motor

neuropathway to increase the muscle spindle intrafusal fiber sensitivity (Myers & Lephart, 2002; Sojka et al., 1991). The pre-activated muscle is therefore stiffer and more responsive to new reflex alpha-motor stimulations since the electro-mechanical delay is lessened (Granata et al., 2000), contributing to greater joint stabilization. Electro-mechanical delay is inversely proportional to muscle stiffness as increased stiffness raises the force generated per unit of stretch, resulting in less time to achieve the desired threshold for force production (Corcos, Gottlied, Latash, Almeida, & Agarwal, 1999; Myers & Lephart, 2002) and joint stability. For example, muscle-tendon reflex mediated electro-mechanical delay has been determined to have a much shorter duration (22.1 ms) than in voluntary muscle contractions (38.7 ms) at the knee joint (Zhou, Lawson, Morrison, & Fairwather, 1995).

Wrist Joint Control

Various densities of mechanoreceptors among all ligaments exist at the wrist. This may imply differential function for wrist stability (Hagert et al., 2005, Hagert et al., 2007). Within the wrist ligaments, the ruffini ending and the pacini corpuscle are the most and least predominant mechanoreceptors, respectively (Hagert et al., 2005). The majority of encapsulated ligament mechanoreceptors are housed within the mid-portion of the

dorsal radiocarpal, intercarpal, and volar triquetro-capito-hamate wrist ligaments (Hagert et al., 2007). Spray-ending type of mechanoreceptors, such as golgi-like receptors and free nerve endings, are widely distributed throughout most of the joint capsule (Lephart & Fu, 2000) and mostly concentrated at the distal portion of ligaments at their bone attachments (Hagert et al., 2007). This topographic arrangement allows for sensory feedback to be generated both in mid and end ranges of wrist ROM (Hagert, 2010) while no afferent input is generated during joint resting conditions (Lephart & Fu). Ligaments at the dorsal radiocarpal and midcarpal joints as well as ulnocarpal and distal radioulnar joints present the most pronounced afferent innervations and are theorized to play a vital role in wrist proprioception and neuromuscular control (Hagert et al., 2007). In contrast, the radial volar ligaments are dense collagenous structures with minimum afferent innervation and their primary function is joint stabilization (Hagert, 2010).

Evidence of a wrist ligament-muscle proprioceptive reflex has been demonstrated between the dorsal scapholunate interosseous ligament and forearm muscles (Hagert, Persson, Werner & Ljung, 2009). When electrically stimulated, the scapholunate ligament induces a monosynaptic reflex within 20 ms that causes a

reciprocal inhibition or excitation of the forearm flexors and extensors, depending on the wrist position. This reflex mechanism, which is speculated to modulate wrist muscle activity via a direct ligament-muscle loop, is accompanied by a polysynaptic co-activation of both flexors and extensors that occur within 50 to 150 ms, resulting in global static wrist stability at any given joint angle (Hagert et al., 2009). This observed latency at the wrist is much longer than expected as compared to the knee where a believed gamma-motor neuron loop reflex mechanism leads to flexor and extensor muscle co-activation with a 22.1 ms electro-mechanical delay (Zhou, et al., 1995). Thus, the direct ligament-muscle reflex loop appears to be a slower than a gamma-mottor neuron loop mechanism for immediate joint stability. Its potential for contributing to joint dynamic stability is secondary to a gamma-motor neuron loop reflex mechanism, which is the first to occur (Myers & Lephart, 2002).

As previously stated, feedforward neuromuscular control involves reflexive muscle spindle pre-activation, which offers improved dynamic joint control as the latency between perturbation and myoelectric event shortens (Granata et al., 2000). Wrist feedforward control is based on previous feedback experiences for motor planning and joint movement execution and control (Hagert, 2010). It produces preparatory muscle activity

and enhances wrist dynamic control via stiffening of the involved tenomuscular units (Simoneau et al., 1999). Such muscle preparatory mechanism utilizes the gamma-motor neuropathway to increase the muscle spindle intrafusal fiber sensitivity (Myers & Lephart, 2002; Sojka et al., 1991). Excitation of the Ia and Ib afferent fibers in wrist muscles lead to joint motor control via reciprocal and recurrent inhibition processes (Bawa et al., 2000; Hagert, 2010). More specifically, the extensor carpi radialis muscle can exert a reciprocal inhibition on the antagonistic function of the flexor carpi radialis muscle during voluntary wrist extension (Hagert). This reciprocal inhibition also occurs in the opposite direction as the flexor carpi radialis muscle inhibits the antagonistic function of the extensor carpi radialis muscle during active wrist flexion (Aymard, Decchi, & Katz, 1997; Bawa et al.; Wargon, Lamy, & Baret, 2006). Reciprocal inhibition is neutralized during co-contraction of the wrist flexors and extensors via complex polysynaptic inhibitory interactions at the spinal cord (Wargon et al.).

Conversely, recurrent inhibition between the flexor carpi radialis and extensor carpi radialis muscles occur during active wrist ulnar and radial deviation (Hagert, 2010). This co-activation pattern is mediated via Renshaw inter-neurons at the spinal cord that prohibit the

inhibitory incoming influence of the Ia and Ib inter-neurons, transforming antagonist muscles to function as synergists (Bawa et al., 2000). Such transformation allows the previously antagonist extensor carpi radialis and flexor carpi radialis muscles to synergistically produce wrist radial deviation while the wrist ulnar deviator muscles are reciprocally inhibited (Aymard et al., 1997).

All of the aforementioned complex sensorimotor processes occur automatically under constant influences from descending supra-spinal pathways that can navigate precise muscle interactions during specific wrist motion demands (Aymard et al., 1997; Chalmers & Bawa, 1997). Similar wrist sensorimotor processes are expected to be initiated during sudden body perturbations that may lead to loss of balance, falls, and wrist trauma. Wrist sensorimotor function during injury conditions has not been studied to date. Further research is needed to determine how the proprioceptive gamma-motor neuron mediated polysynaptic mechanism as well as reflex reciprocal and recurrent inhibition processes contribute to wrist joint dynamic control during conditions that may result in wrist fracture.

Pain Influence on Sensori-Motor System

Neuroanatomy

Sensations of pain, joint position and motion are centrally processed via two anatomically exclusive but interrelated ascending pathways (McCloskey, 1978; Besson & Chaouch, 1987). Pain input involves the neo- and paleo-spinothalamic systems. These two systems transmit fast and slow pain impulses from the peripheral limp nociceptors to the central nervous system. First-order neurons of the neo-spinothalamic tract carries fast pain impulses to the dorsal horn of the spinal cord from type-Aδ peripheral nociceptors, which specialize on acute, sharp and well localized pain sensations. Second-order neurons originate in the dorsal horn, cross over to the contralateral side of the spinal cord, enter the anterior-lateral faniculus and ascend to the ventral posterior-lateral (VPL) nucleus of the thalamus. Third-order neurons extend from the thalamus to the primary sensory cortex for precise pain intensity and location interpretation. Neurons of the paleo-spinothalamic tract, which carry slow pain impulses from type-C peripheral nociceptors, follow the same ascending pathway, and terminate in the ventral posterior-lateral nucleus of the thalamus (Besson & Chaouch). This pathway lacks upper cortical connection and thus is responsible

for only diffuse, dull and poorly localized pain sensations (Guyton, 1991).

The joint position and motion sense ascending pathway involves the dorsal column system, which transmits somatosensory impulses from the peripheral limp mechanoreceptors to the central nervous system (McCloskey, 1978; Young and Young, 1997). First-order neurons of this tract carry tactile, vibration, and limp position and motion proprioceptive impulses from the periphery to the dorsal horn of the spinal cord where they can synapse with the incoming spinothalamic fibers for reflex pain modulation. Second-order neurons start at the dorsal horn, enter the posterior faniculus and ascend to the cuneate and gracile nuclei at the medulla. Third-order neurons originate from the cuneate and gracile nuclei, cross the midline and ascend the brain stem anterior-medially through the medial lemniscus tract, which also terminates at the VPL nucleus of the thalamus (Wall, 1970; McCloskey). At the thalamus, tertiary axons intermingle with the incoming neo-spinothalamic tract pain fibers and ascend to the primary sensory cortex for precise interpretation (Young and Young).

The cerebral cortex is characterized by 50 distinct anatomic regions known as Brodmann areas based on their structural and functional differences. Among these regions, the primary sensory cortex is located at the

parietal lobe posterior to the central fissure of the cerebral cortex and consists of the Brodmann areas 1, 2 and 3 (Guyton, 1991). The primary sensory cortex processes all sensory modality signals that ascend via the spinothalamic and dorsal column pathways and it is divided into two distinct regions: somatic sensory areas I and II. The somatic sensory area I has the most critical role for body's sensory function. It contains distinct spatial somatotopic representations for each body region. These representations are proportional to the amount of sensory input is derived from each body area. In example, the upper extremity and the hand are represented by a disproportionately very large area as compared to the remaining of the body due to the extensive discriminatory sensory inputs deriving from their proprioceptive and nociceptive receptors (Goldman-Rakic, 1988).

Somatic sensory areas I and II have distinct functions. The function of the somatic sensory area I is to provide discrete sensation localization as well as precise appreciation for the quality and intensity of each sensory modality. In contrast, the somatic sensory area II is a very small area, which function is poorly understood. It receives only a small proportion of ascending sensory pathways and offers poor degree of signal localization and discrimination (Guyton, 1991).

The somatic association area consists of Brodmann areas 5 and 7 and is located posterior to the somatic sensory areas I and II. It communicates with the primary sensory cortex to critically analyze and interpret multiple or complex sensory information that often relate to the senses of body proprioception (McCloskey, 1978). The primary motor and pre-motor cortices are located anterior to the central fissure of the cortex in Brodmann areas 4 and 6, and they contain a topographic representation of different body muscle regions. These areas generate a multitude of discrete motor signals for detailed body movement (Guyton). They also function in concert with the primary sensory cortex and cerebellum (Blakemore, Frith & Wolpert, 2001; Riemann & Lephard, 2002b) to direct conscious and unconscious sensori-motor responses for dynamic joint control (Myers & Lephart, 2002; Hagert, 2010).

Neuroplasticity Mechanisms

Neuroplasticity is defined as a central adaptation process in which both healthy and damaged brain tissue undergoes morphologic changes in response to new or lack of afferent stimuli influx (Pascual-Leone, Amedi, Fregni & Merabet, 2005). It encompasses critical functional and structural neural tissue reorganization that can naturally occur throughout the entirety of the central nervous system during exposure to new sensory or motor

skills and experiences as well as following peripheral or central nervous tissue insult (Westlake & Byl, 2013). Since the early observations of Hebb (1949), it has been known that there is a potential of plastic adaptations via synaptogenesis (i.e., enhancement of new neuro-synaptic connections) and increase of axonal dendritic branching within the central nervous system. This was known as Hebbian plasticity, which was described as an activity-dependent plastic reorganization neural growth process that occurs over time in post-synaptic nerve cells upon being constantly stimulated by their pre-synaptic counterparts (Westlake & Byl).

Central neuroplasticity can occur via both transitional- and permanent-change processes following peripheral nerve lesion (Westlake & Byl, 2013). Initially, decreased somatosensory input from tissues with a peripheral nerve lesion leads to a selective somatotopic adaptation changes at the cortex. The primary sensory cortex area that corresponds to injured peripheral region becomes deprived and silent due to lack of sensory input. Concurrently, a long-term potentiation process is initiated, which promotes cortical excitatory activity adjacent to the deprived somatosensory area of the cortex. This process is characterized by increased neuro-synaptic sensitivity and strength as well as a somatotopic boundary expansion. Thus, a cortical

remapping occurs with intact somatosensory regions being potentiated and expanded into adjacent cortical regions that represent injured peripheral sites, accommodating for their deprived cortical function (Ziemann, Hallett & Cohen, 1998). Ultimately, transitional changes are followed by permanent morphological cortical adaptations in plasticity that are characterized by synaptogenesis and increase of axonal dendritic branching within the potentiated somatosensory cortical regions (Kleim et al., 1998; Kleim et al., 2004; Johansson & Belichenko, 2002).

Synaptogenesis and dentritic branching are two comparable processes of neuroplasticity that have been observed at the supra-spinal (i.e., cortex, thalamus and cerebellum) and spinal cord levels, and are implicated to central reorganization following peripheral nerve lesions with loss of sensory influx and altered motor control (Adkins, Boychuk, Remple & Kleim, 2006). Synaptogenesis refers to multiplication or creation of new excitatory synapses among interacting neurons within potentiated central regions (Kleim et al., 2004). Dentritic branching refers to creation of new axonal dendrites, ultimately leading to increase in both neuro-synapses and post-synaptic contacts among interacting neurons (Johansson & Belichenko, 2002). Both of these processes are thought to play a crucial role in the reorganization of central sensory and motor neuro-circuits that control motor skill

retraining following peripheral injury (Adkins et al.). Dendritic branching of the dorsal root axons in the spinal cord was first reported by Liu and Champers (1958). However, later studies demonstrated that such neuroplastic adaptations within the spinal cord are minimal (Kerr 1972), only possible in unmyelinated axons (Hul-sebosch & Coggeshall, 1981) and probably implicated in the strength of reflex motor outputs following peripheral nerve injury (Adkins et al.). Essentially, all of the aforementioned processes become of particular importance in restoring the complex feedback and feedforward reflex sensori-motor mechanisms that become impaired following upper extremity trauma (e.g., DRF).

Pain-Induced Neuroplasticity

According to Merskey and Bogduk (1994) pain is a multidimensional brain output, which is more than just an unpleasant sensory encounter related to real or potential tissue damage. Melzack (1996) and Moseley (2003) agreed that pain experience entails an individual-based neuromatrix of both sensory and non-sensory domains. The sensory domain of pain is characterized by sub-cortical and cortical pathways that mediate and produce pain upon tissue insult. Non-sensory domain consists of physiological and emotional reactivity to pain experiences. Physiological responses to pain include decreased cortical processing ability (Derbyshire, Vogt,

& Jones, 1998; Luoto, Taimela, Hurri & Alaranta, 1999), increased rate of cognitive error (Buckelew, De Good, Schwartz, & Kerler, 1986), slower ability to decision making (Crombez, Eccleston, Baeyens, & Eelen, 1996), loss of concentration and increased memory loss (Jaminson, Sbrocco, & Parris, 1988; Schnurr & MacDonald 1995), and decreased neuromuscular responses or modulation of motor strategies (Lund, Donga, Widmer, & Stohler, 1991; Zedka, Prochazka, Knight, Gillard, & Gauthier, 1999; Moseley). The emotional response to pain indicates the need for attention and awareness to an unpleasant experience (Merskey & Bogduk, 1994). It also relates to other affective-emotional dimensions of anxiety, fear, and anger (Osuch et al., 2000).

Research evidence exists to support that persistent input of nociceptive signals following injury can lead to central nervous system neuroplasticity (Elbert et al,. 1997; May, 2008), including cortical (i.e., thalamus, and primary sensory cortex) and sub-cortical centers (i.e., dorsal horn; Flor et al., 2006; Price et al., 2006; Anderson et al., 2006; Borsook, 2007, May). There are several physiological, biochemical, and cellular mechanisms that induce central plasticity in response to peripheral nociception following tissue injury. Once central neuroplasticity develops, it can further contribute to the propagation of pathologic pain

processes that lead to pain threshold reduction and evoke central pain hypersensitivity and hyperalgesia (Coderre, Katz, Vaccarino & Melzack, 1993).

Several studies have demonstrated physiological central nervous system reorganization processes following tissue injury and nociception in the animal model (Wall, Cusick & Kaas, 1981; Kelahan & Doetsch, 1981; Rasmusson 1982; Merzenich et al., 1983). Cortical reorganization processes have been clearly demonstrated in Brodmann areas 1 and 3 of the somatic sensory cortex, where the hand and upper extremity have an extensive representation. These processes are analogous and in addition to the earlier described neuroplasticity processes in response to lack of afferent stimuli. There is variability in types of cortical reorganization in response to a peripheral noxious injury, which may include somatotopic and repetitive expansions, formation of new representation, and incomplete or non-topographic reactivations. Essentially, central plasticity depends on various neural transformation processes that renders previously inadequate synapses more effective or sensible as well as promotes cortical expansion and reorganization via neural axonal growth and/or dendritic branching (Kaas, Merzenich & Killackey, 1983).

Merzenich et al. (1983) was the first to determine that somatotopic cortical reorganization can occur in

adult owls, squirrels and monkeys following median nerve resection. The initial sensory deprivation of the cortical regions representing the median dermatome of the hand was followed by a gradual somatotopic expansion of adjacent cortical regions into the deprived cortical areas. In some instances, this led to full topographic reorganization in which some hand skin areas were shifted entirely into the deprived cortex. In other instances, repetitive expansions occurred when different segments of the deprived cortex presented nearly identical or overlapping receptive fields from the same hand skin areas. New representations of deprived hand segments also re-appeared either at remote areas or their exact original location within the deprived cortex following their pre-injury somatotopic organization. In this study, full reactivation of the deprived cortex representing hand fields occurred following sufficient recovery time.

Incomplete cortical reactivation is also possible. This occurs when certain deprived areas of the cortex may be more difficult to reorganize as they maintain lower neuronal activity following injury deafferentation (Kaas et al., 1983). Incomplete cortical reorganization has been reported in the receptive cortical fields of the foot after sciatic nerve recection among rats despite the initiation of central processes towards expanded cortical representation (Wall et al., 1981). In other instances,

non-topographic reactivation may also occur. This type of cortical reorganization has been reported by Kelahan and Doetsch (1981), Rasmusson (1982), and Merzenich et al. (1983) who discovered that a digit amputation of an adult raccoon or monkey induced deprivation at the amputated digit cortical fields followed by cortical re-activation, which was mediated by skin regions of the adjacent digits. These researchers concluded that topographic re-organization did not occur within the deprived cortex region. Rather, representation of the amputated digit evolved within the boundaries of non-affected cortical centers.

Biochemical mechanisms that contribute to central plasticity in response to noxious stimulus consist of the C-fiber neuropeptides and excitatory amino acids activity (Coderre et al., 1993). C-fiber neuropeptides that include substance P (Go & Yaksh, 1987), neurokinin A (Hua et al., 1986), somatostatin (Morton, Hutchison, & Hendry, 1988), calcitonin gene-related peptide (Saria et al., 1986), and galanin (Morton and Hutcison, 1990) are released in the spinal cord dorsal horn following peripheral injury and nociception. The presence of C-fiber neuropeptides causes an initial excitation (Henry 1976) followed by increased depolarization of dorsal horn neurons (Murase & Randic, 1984) and distortion on spinal reflex mechanisms (Woolf & Wiesenfeld-Hallin, 1986).

Comparable effects are produced by the release of excitatory amino acids (Skilling, Smullin, & Larson, 1988), which lead to receptive field distortion (Zieglgansberger & Herz, 1971) and excessive excitability to both noxious and non-noxious stimulus at the spinal cord dorsal horn neurons, leading to central hyperalgesia (Aanonsen, Lei, & Wilcox, 1986).

Cellular mechanisms of central neuroplasticity, which are induced by noxious signal, have also been proposed (Coderre et al., 1993). Neuropeptides and excitatory amino acids activity induce alterations in neurons membrane excitability via interactions with neurotransmitters and second messenger systems throughout the central nervous system (Nestler & Greengard, 1983). This produces an increase of intracellular calcium and other ions influx, which influences cell excitability threshold and post-synaptic inter-cellular communication capacity (MacDermott, Mayer, Westbrook, Smith & Barker, 1986). Furthermore, a phospholipase C second massager system activation can promote additional release of intracellular calcium via interactions with protein kinase C enzyme, which has an established role in increasing the neuronal excitability status of cortical regions during the long-term potentiation process (Malenka, Madison, & Nicoll, 1986).

Direct evidence of cortical reorganization in the human brain has been demonstrated on amputees and patients with complex regional pain syndrome. Amputation leads to deafferentation of the limb's cortical representation followed by phantom kinesthetic sensations, awareness of limb existence, and pain from the missing limb. Central as well as peripheral mechanisms are implicated as determinants to phantom limb pain following amputation (Flor et al., 2006). Retrograde degeneration of peripheral afferent neurons, regenerating axonal sprouting (Blumberg & Janig, 1982), and ectopic discharges from stump neuromas represent types of abnormal afferent input to central nervous system following amputation (Nystrom & Hagbarth, 1981). Ectopic discharges occur in the dorsal root ganglion in response to neuroma activity in the stump, leading to activation of spontaneous sympathetic response or spinal hyper-excitability at the spinal cord (Chen, Michaelis, Janig & Devor, 1996). Neuroplastic supraspinal reorganization changes that result from phantom limb pain follow and involve the brainstem, thalamus and cerebral cortex (Davis et al., 1998; Wu & Kaas, 1999). Evidence for cortical reorganization has been provided by Knecht et al. (1996), Birbaumer et al. (1997), and Elbert et al. (1997) who determined that significant somatotopic expansion of the somato sensory cortex area corresponding

to the face occurs within the cortical region representing the absent limb following upper extremity amputation.

Complex regional pain syndrome has also been implicated in causing central neuroplastic changes in humans involving receptive deafferentation alterations in the cortex. Maihofner, Handwerker, Neundorfer and Birklein (2003) determined that a significant shrinkage of the cortical somatotopic fields representing the hand had occurred among patients with upper extremity complex regional pain syndrome. They demonstrated via magnetic imaging significant somatic sensory cortex shifting of the fields representing the hand into adjacent cortical regions representing the face and lips. Similarly, central reorganization and impaired proprioceptive acuity has been proposed to be one of the main reasons for the neglect or delayed response among complex regional pain syndrome patients to recognize their affected hand (Moseley, 2004).

Pain-Induced Proprioceptive Impairment

Advances in neuro-imaging studies have led to strong evidence of brain alterations in structure and function in response to musculoskeletal pain (Maihofner et al., 2003; Diers, Christmann, Koeppe, Ruf, & Flor, 2010). This growing research evidence suggests that peripheral tissue

injury and pain result in central maladaptive neuroplastic changes leading to interference with proper integration and interpretation of reflex sensori-motor pathways (Borsook, 2007). Numerous studies have implicated the aforementioned hypothesis to unconscious and conscious proprioception sense deficits following musculoskeletal trauma. Among these studies, heavy research emphasis has been directed towards deficits in motor control of the trunk in low back pain patients who seem to be characterized by altered cortical responses to noxious stimulus (Wand et al., 2011).

Hodges and Richardson (1996) conducted an electro-myographic study to determine the sequence of trunk muscle activity in response to trunk disturbance associated with arm movement among patients with low back pain. They concluded that the preparatory contraction of the transversus abdominis muscle was significantly delayed in low back pain patients as compared to the matched control participants. Similar findings were reported by Hodges and Richardson (1998) who used the same methodology to study the preparatory neuromuscular response of trunk muscles associated with lower extremity movement in low back pain patients. They determined that feed-forward postural responses of the transversus abdominis muscle was significantly delayed in all lower limb movements as compared to other trunk muscles (i.e.,

rectus abdominis, erector spinae and obiques), which were delayed in selected movements only. Hodges and Richardson (1999) conducted an EMG study to compare the trunk neuromuscular control in response to varying speeds of upper extremity movements in patients with and without low back pain. Their results indicated that their participants failed to demonstrate early preparatory transversus abdominis and internal oblique muscle activity during rapid upper extremity motions. Impaired postural control was attributed to a centrally controlled proprioceptive deficiency. A similar study by Hodges and Richardson (2003) aimed to determine whether the recruitment of various trunk muscles is altered by experimentally induced low back pain during a postural task controlled by repetitive arm motion. Their results reconfirmed that delayed trunk muscle recruitment (i.e., transversus abdominis, internal and external obliques, and multifidus muscles) is linked to inhibition of central feed-forward and motor planning mechanisms. Moseley, Nicholas and Hodges (2004) also added that both low back pain and emotional stress lead to delayed deep trunk muscle activations. The patho-physiology of the aforementioned assertions were supported by Tsao, Galea, and Hodges (2008) who determined that patients with low back pain had a shifted topographic representation for

the transversus abdominis contraction in the motor cortex.

The relationship between knee proprioception deficits and osteoarthritis has been emphasized by early research. Cross sectional studies by Skinner et al. (1984); Barrett et al. (1991); and Sharma and Pai (1997) have demonstrated that both kinesthesia and JPS abilities were significantly reduced among elderly osteoarthritis patients compared to their age-matched asymptomatic controls. The hypothesis that patellofemoral pain is associated with delayed activation of the vastus medialis obliquus muscle due to an altered reflex neuromuscular control pathway during a functional task (i.e., stair climbing) has also been determined by Cowan et al, (2001). On the basis of these data, Baker et al. (2002) compared the JPS of participants with and without patelo-femoral pain. They studied both weight and non-weight bearing conditions at various knee angles. Their results indicated that participants with knee pain had significantly less accurate JPS responses in both weight- and non-weight bearing conditions than their asymptomatic counterparts. They concluded that proprioception loss could be intrinsically linked to a pain-driven central reflex mechanism that leads to abnormal motor control.

Pain is a clinically meaningful impairment following DRF (MacDermid et al., 2002; MacDermid et al., 2003;

Karagiannopoulos et al., 2013) due to its influence on wrist sensori-motor control (Karagiannopoulos et al.) and patient function (Harris et al., 2005). A recent cross-sectional study by Karagiannopoulos et al. determined that significant wrist active JPS deficit exists among older females 8 weeks following distal radius fracture (DRF) surgical and non-surgical intervention. In this study, a significant positive correlation existed between pain and active wrist JPS deficits. However, the magnitude of pain effect on conscious and unconscious sensori-motor control following DRFs has yet to be determined. It is imperative as we explore more about the influence of pain on central nervous system changes, to acquire more knowledge on how pain following DRF leads to neuroplasticity, resulting in loss of wrist joint dynamic control. As this process is in its infancy, further research is needed to explore the explicit patho-physiology for the altered wrist proprioception following DRFs.

Epidemiology of Distal Radius Fractures

DRF is defined as a metaphysial bone fracture that usually occurs within the distal 3 cm of the radius (Handoll, and Madhok, 2003a) among adults that are still healthy, active, and functionally independent (Cummings, Black, & Rubin, 1989; Kelsey, Browner, & Seeley, 1992).

DRF are most commonly seen among older but otherwise healthy adults (Ring & Jupiter, 2005), especially after the age of 65 (Vogt et al., 2002). The population of older healthy and active adults has been steadily increasing since the 1940s as a result of increasing birth rates, healthier lifestyles, and improved health care (Ring & Jupiter). According to the United States Census Bureau (2000), the 65 years of age or older population is estimated to increase from 12 to 20% by 2030. As this population continues to grow, the number of osteoporotic DRFs is also expected to increase exponentially (Ring & Jupiter).

Injury mechanism

The leading cause of DRF is high-energy trauma among young adults (Chen and Jupiter, 2007) and low-energy trauma among older age groups (Handoll, Madhok, Howe, 2006). DRF prevail among older caucasian females (Raia & Catalano, 2007) who frequently sustain unexpected low energy falls on an outstretched arm from a standing position (Handoll et al.), resulting in a wrist hyperextension moment (Chen and Jupiter). Wrist sensorimotor function during an unexpected fall injury conditions that result in a DRF has not been studied to date. In theory, both reactive preparatory feedforward and feedback mechanisms are expected to be activated at the wrist for joint control during this type of injury

mechanisms. During a fall and as the upper extremity is striking the ground, supraspinal feedforward mechanisms are expected to activate pre-stored motor programming and gamma-motor pathways (Myers & Lephart, 2002; Sojka et al., 1991), producing anticipatory wrist muscle activity that enhances dynamic joint control via stiffening of the involved wrist tenomuscular units (Simoneau et al., 1999).

Despite the level of responsiveness offered by an intact wrist sensorimotor system, a fracture occurs when compression forces exceed the distal radius maximum bone-yield capacity. Typically, the distal radius reaches first its maximum bone-yield capacity at its inertly weaker metaphysial region where most compressive forces are transmitted through the dorsal articular surface of the radiocarpal joint (Chen and Jupiter, 2007). The distal radius metaphysial cortical bone mass decreases to 30 to 50 % in comparison to its diaphysial region, which is formed by 95% of cortical bone mass. The majority (50 to 70 %) of the distal radius bone mass is formed by weaker trabecular bone forming a zone velnurable to fracture (Cummings, Kelsey, Nevitt, & O’Dowd, 1985). Thus, when compressive forces are redirected through this weaker trabecular bone zone, fracture lines frequently propagate between the scaphoid and lunate facets within the distal radius articular surface (Simic & Weiland,

2003). Dorsal radio-carpal joint compressive forces occur along with increased tensile forces within the extrinsic wrist flexor tendons and radiocarpal, ulnocarpal, and intercarpal ligaments, rendering them vulnerable to potential injury (Chen and Jupiter).

Prevalence and Incidence

According to the United States Center of Disease Control and Prevention (1996) an estimated 850,000 fractures occur annually in the United States among persons aged 65 years or older. DRF constitute approximately 18% of all body fractures (Kulej, Dragan, Krawczyk, Orzechowski, & Plochowski, 2008), is the most common upper-extremity fracture in adults aged 65 years or older (Gehrmann, Windolf, & Kaufmann, 2008), and is one of the most common fractures encountered in emergency orthopedic care (Raia & Catalano, 2007). The total Medicare cost during the 12-month period (July 1991 through June 1992) following a wrist fracture is estimated to be $2,564 per patient at 65 years of age or older (U.S. Center of Disease Control and Prevention, 1996).

DRF incidence is age and gender specific. It occurs frequently among adults during the second and third decades of life, sharply increasing after the fifth decade of life (Solgaard & Petersen, 1985), especially among women (Bengner & Johnell, 1985). Up to 30 years of

age, DRFs seem to occur slightly more frequently among males than females (Schmalholz, 1988). During this early period, males are 1.4 times more likely to sustain a DRF than females. The DRF incidence rate remains similar between genders in the 30 to 45 years age cohort (Singer, McLauchlan, Robinson, & Christie, 1998). Thereafter, the risk of sustaining DRF increases with advancing age among women (Lippuner, Johansson, Kanis, & Rizzoli, 2009). The incidence of DRF among caucasian females in the United States and Northern Europe starts increasing at the age range of 45 to 50 years, and the risk of sustaining a DRF by the age of 50 is estimated to be 15 and 2% for females and males, respectively (Cummings et al., 1989). Incidence of DRF reaches maximum levels at 65 years, (McQueen & Court-Brown, 2003; Singer et al.). The probability of sustaining a DRF at 50 years of age and older is estimated to be 20 and 51% for males and females, respectively (Lippuner et al.). DRF incidence among caucasian females remains unchanged up to 75 years of age (Schmalholz), with females being 2.3 times more likely to sustain a DRF (Singer et al.). DRF incidence among women declines slightly after the age of 75. In contrast, the DRF incidence among males remains constant at low levels up to 85 years of age (Schmalholz) and increases slightly thereafter (Singer et al.).

Vogt et al. (2002) conducted a multicenter 10-year prospective cohort study on 9,704 DRF patients who were recruited from 1986 to 1988 in seven east and west coast states of the United States. They reported the incident rate among white females aged 65 years or older to be 8 to 10 per 1,000 person-years. United States Center of Disease Control and Prevention (1996) reported that the incidence of DRF from July 1991 through June 1992 was 37.8 per 10,000 people. The DRF incidence among white and black adults aged 65 years or older was 39.6 and 17.3 per 10,000 people, respectively. Within the same period, DRF incident rates among female and male adults aged 65 years or older were 54.0 and 11.7 per 10,000 people, respectively.

The aforementioned DRF incidence rates are comparable to the results of another multicenter prospective study conducted between 1997 and 1998 among 3,161 British women and men aged 35 years or older. During this 12-month period, the incidence of DRF was estimated to be 36.6 per 10,000 persons per year among females and 9.0 per 10,000 persons per year among males with a female to male ratio of 4:1 (O’Neill et al., 2001). In another British multicenter prospective cohort study of 1,300 DRF patients over the age of 25 years, the incidence of DRF among females rose from a premenopausal level of 10 per 10,000 persons per year to 120 per 10,000

persons per year for those over the age of 85 years. Among males, the fracture incidence increased from 10 per 10,000 persons per year before the age of 65 years to 33 per 10,000 persons per year after the 85 years age mark (Thompson, Taylor, & Dawson, 2004).

Risk Factors

Age, gender, and bone mineral density levels are the most documented risk factors associated with DRF (Kelsey et al., 1992; Lippuner et al., 2009; Singer et al., 1998; Vogt et al., 2002). At the age of 50 years and older the absolute 10-year probability of obtaining an osteoporotic DRF increases with advancing age and decreasing bone mineral density, and is higher in women than men (Lippuner et al.) with a female to male ratio of 4:1 (Thompson et al., 2004). Low bone distal radius mineral density, history of recurrent falls, and having had a previous fracture after the age of 50 are strong independent predicting factors for DRF among adults 65 years and older (Vogt et al.). About 33% of all women above 64 years of age sustain a low-energy fall annually. Only 1 to 2% of these falls result in a DRF (Tinetti, Speechly, & Ginter, 1988) with the strongest predicting risk factor being low-bone mineral density (Vogt et al.). Other independent predicting factors for DRF are poor visual acuity and lack of frequent walking (Kelsey et al.).

Osteoporosis, although widely predominant among women, is an age-related condition that results in higher rates of morbidity and mortality in both genders due to decreased bone density (U.S. Center for Disease Control and Prevention, 1996; Ring & Jupiter, 2005). Osteoporosis can be classified in two types. Type I osteoporosis is associated with accelerated loss of trabecular bone, leading to fractures at skeletal sites containing large amounts of trabecular bone, such as the distal radius. Type II osteoporosis presents a more gradual diminishing of both trabecular and cortical bone, leading to fractures at the hip, pelvis, proximal humerus, and vertebrae bodies. Type I osteoporosis mainly affects women within 25 years of menopause and is linked to diminishing estrogen levels. Type II osteoporosis affects both genders older than 75 years old and is related to aging (Eastell, Wahner, O'Fallon, Amadio, Melton, Riggs, 1989).

Osteoporosis is a major cause of DRF, especially among females and older age groups (Chen and Jupiter, 2007; Earnshaw, Caute, & Worley, 1998). Trabecular bone loss at the distal radius begins in young age for both genders and continues throughout life. Before the age of 50, females and males reach 37 and 42% of their total lifetime trabecular bone loss, respectively. However, females present a disproportionate acceleration of

trabecular bone loss at the distal radius at menopause, which is associated with decreased estrogen levels (Riggs et al., 2008). DRF threshold has been determined to be 0.40 g/cm² units of bone mineral density. The lower the bone mineral density below this threshold the greater the risk of DRF (Eastell, Riggs, Wahner, O'Fallon, Amadio, Melton, 1989) or subsequent osteoporotic fractures later in life (Kulej et al., 2008; Parkinson & Fazzalari, 2008). Incidence of osteoporotic DRF peaks 5 to 10 years earlier than the incident of spine and hip fractures for both genders (Parkinson & Fazzalari).

Sustaining a DRF following low-energy trauma is also viewed as an early manifestation of post-menopausal osteoporosis among females (Cuddihy, Gabriel, & Crowson, 1999). Over 50% of females 40 years or older who sustain a DRF are also diagnosed with osteoporosis (Earnshaw et al., 1998). In contrast, smaller proportions (nearly 42%) of male patients who sustain a DRF are diagnosed with decreased bone mineral density at the distal radius than their age and gender matched healthy counterparts (Tuck, Raj, & Summers, 2002).

Distal Radius Fracure Classification and Radiological Assessment Factors

Assessing DRF is a multi-faceted process with the primary objective of determining an efficacious treatment

for the most optimal functional outcome (Chen & Jupiter, 2007). Determining proper treatment post DRFs is multi-factorial and encompasses patient life-style and characteristics, fracture displacement and stability, and other concomitant patient co-morbidities (Ilyas & Jupiter, 2007). Radiological information has been traditionally used to classify DRFs, grade their severity level, and guide post-fracture management. Newly improved imaging (e.g., three-dimensional computed tomography) have also led to enhanced understanding of DRF morphology, guiding treatment decisions towards more advanced surgical interventions (Chen & Jupiter). Although radiological assessment has its merits with respect to attaining the aforementioned objectives, its ultimate objective, to offer strong predictive evidence towards long-term functional recovery post DRFs, has been questioned by recent studies (Chung, Kotsis & Kim, 2007; Karnezis, Panagiotopoulos, & Tyllianakis, 2005).

Classification Systems

The term “Colles’ fracture” constituted the earliest DRF classification system. This system was created in 1814 nearly 80 years before x-ray was invented (Laseter & Carter, 1996) when Abraham Colles published his work “on the fracture of the carpal extremity of the radius”. His intent was to describe dorsally displaced and unstable DRFs assessed simply based on appearance. The primary

mechanism was due to a fall on an outstretched arm, frequently resulting in a deformity that remained unresolved throughout a patient's life. Since then, the term Colles' fracture has been used to describe a DRF with an obvious dorsal wrist angulation known as a "dinner fork deformity", which is associated with dorsal displacement of the distal radius fragment, dorsal comminution, and radial shortening (Handoll & Watts, 2008).

Although Colles' fracture was originally considered to be an extra-articular, minimally displaced, and stable bone injury (Laseter & Carter, 1996), more advanced radiologic techniques have revealed numerous other DRF characteristics and patterns not consistent with the Colles' fracture original description (Handoll & Watts, 2008; Laseter & Carter). The term "Barton's fracture" was established by Barton (1838) to describe an unstable shearing intra-articular DRF with a dorsal or volar displacement of the distal radius articular margin along with carpus subluxation. The term "reverse Barton's fracture" was introduced by Thompson and Grant (1977) to designate only the volary displaced Barton's fracture type (Harness, Ring, & Jupiter, 2004). The term "Smith fracture" was introduced by Smith and Floyd (1988) to

further sub-classify volary displaced non-articular DRFs without carpus dislocation (Thivaios & McKee, 2003).

Various fracture patterns have been incorporated into numerous DRF classification systems published through the years (Handoll & Watts, 2008; Ilyas & Jupiter, 2007). These include the Gartland and Werley (1951); Lidstrom (1959); Older, Stabler, and Cassebaum (1965); Frykman (1967); Melone (1984); McMurtry and Jupiter (1991); Swiss Association for the Study of Internal Fixation (AO/ASIF) group (Muller, Allgower, Schneider, & Willenegger, 1991); Universal Classification (Cooney, 1993); and Fernandez (Fernandez, 1993) classification systems. Among them, the Frykman and AO/ASIF are two of the most frequently documented classification systems in the recent DRF literature (Laseter & Carter, 1996). Although there is no clear documented justification for their pronounced popularity, both of these classification systems are thought to offer a broader classification framework based on numerous fracture characteristics, including extra- and intra-articular patterns, presence of distal ulnar involvement, and degree of distal radius comminution and angulation.

Gartland and Werley (1951) determined that a large percentage (88%) of DRFs is intra-articular with approximately one third leading to poor functional

results. They classified DRFs based on the presence or absence of an intra-articular component. Lidstrom's (1959) proposed that, in addition to the extent of articular involvement, DRFs should be classified by the nature of the fracture line, direction of displacement of the distal fragment, degree of fragment displacement, and involvement of the distal radioulnar joint. Older et al. (1965) further classified DRFs into four types based on increasing severity of radial shortening as well as distal radial fragment displacement, comminution, and dorsal angulation.

The Frykman (1967) classification system subdivides DRFs into eight groups, depending on the involvement of the distal radioulnar and radiocarpal joints, and the concomitant presence or absence of a distal ulnar fracture. In this classification system, groups 1 and 2 encompass less severe extra-articular DRFs with and without distal ulna fracture involvement, respectively. Groups 3 and 4 incorporate more complicated intra-articular DRFs that pass through the radiocarpal joint with or without distal ulnar fracture involvement, respectively. Groups 5 and 6 include more severe intra-articular DRFs through the distal radioulnar joint with or without distal ulnar fracture involvement, respectively. Finally, groups 7 and 8 involve the most

severe intra-articular DRFs that pass through both aforementioned joints with or without distal ulnar fracture involvement, respectively.

Melone (1984) identified four distinct parts of the radiocarpal joint that can be involved in an intra-articular DRF. These parts include the distal radial shaft, radial styloid process, a dorsal-medial fragment and a palmar medial fragment. In his later publication (Melone, 1993), Melone classified DRFs into five types, based on the degree or direction of displacement of the previously described four intra-articular components. McMurtry and Jupiter (1991) provided an operational definition for intra-articular DRFs as those that extend into the radiocarpal or the distal radioulnar joint and present an intra-articular step-off greater than 1 mm. They classified DRFs into four types, based on the inta-articular fragment size and its potential to be surgically repaired.

Muller et al. (1991) published the AO/ASIF classification system which categorizes DRFs into three types (A, B, C) with three subdivisions within each type (1, 2, 3) and three fracture levels within each subdivision. This complex classification system consists of 27 total fracture subgroups, based on extra-articular, simple articular, and complex intra-articular DRFs with

increasing severity and complexity from A1 to C3 levels (Ilyas & Jupiter, 2007). The extra-articular type neither affects the distal radioulnar nor the radiocarpal joints. This type is divided into three sub-categories (A1, A2, A3), based on distal radius exclusion or inclusion and its fragmentation level. Furthermore, each A subcategory contains three fracture levels based on the presence or absence of ulnar metaphyseal or styloid fragments, radial tilt, and radial shortening (Laseter & Caster, 1996).

The second type in the AO/ASIF classification system is the simple articular DRF. This type partially affects the distal radioulnar and radiocarpal joints without disruption of the radius metaphysis and epiphysis continuity and is divided into three subcategories (B1, B2, B3), based on the direction of the fracture line through the radial dorsal, volar, or sagital rims. Each B subcategory contains three fracture levels, based on radius fragmentation severity levels. Finally, the complex articular type affects both the distal radioulnar and radiocarpal joints and is divided into three sub-categories (C1, C2, C3), based on radius metaphyseal fragmentation severity. Each C subcategory involves three fracture levels, based on the geometric complexity and location of the distal radius intra-articular fragment (Laseter & Caster, 1996).

Cooney (1993) expanded on the Gartland and Werley (1951) earlier classification system, structuring a universal classification system, based on four treatment criteria related to fracture reducibility. In his treatment algorithm, DRFs are first categorized as extra- or intra-articular and further subdivided within each category as non-displaced or displaced. Non-displaced extra- or intra-articular DRFs require cast immobilization. Displaced extra-articular DRFs identified as stable fracture require cast immobilization. Displaced extra-articular DRFs identified as unstable fracture require stabilization with percutaneous pinning. Displaced intra-articular DRFs are identified as reducible via an external fixator or non-reducible, requiring an open-reduction and internal-fixation approach.

The Fernandez (1993) classification system is based on five specific types of DRF injury mechanisms, which are unrelated to bone displacement and fracture line location. Type I describes a bending mechanism of the distal radius with the metaphysical cortex undergoing either tensile or comminuting forces at opposite sides. Type II describes a shearing fracture mechanism which results in a volar or dorsal distal radial fragment dislocation. Type III denotes a compression fracture mechanism which leads to distal radius impaction or

comminution with intra-articular involvement. Type IV projects an avulsion fracture mechanism involving either the radial or ulnar styloid processes. Type V is based on combination of the aforementioned fracture mechanisms occurring in high energy injuries with extensive trauma.

Radiologic Assessment Factors

As the aforementioned classification systems have helped physicians guide their treatment decision, there are other radiological factors (i.e., radial inclination, palmal tilt, radial shortening, dorsal angulation, articular step-off) that need to be considered to maximize DRF treatment efficacy and patient functional recovery (Laseter & Carter, 1996). These important radiological factors are typically assessed via posterior-anterior and lateral x-ray views of the wrist (Souer, Ring, Matschkes-Audige, Marant-Hubert, & Jupiter, 2009). Correlating DRF radiological classification with patient outcomes has been controversial. The AO/ASIF classification system is not correlated with patient-reported outcomes of the Patient Rated Wrist Evaluation (PRWE) scale when radiographs are taken at initial fracture presentation (Karnezis et al., 2005). In contrast, Barton, Campers, and Bannister (2007) reported a significant ($p = 0.037$) but moderate correlation ($r = .30$) between the Frykman's DRF classification and patient-reported outcomes of the PRWE scale when

radiographs are taken at the time of fracture union after treatment. Significant association ($p = 0.02$) has been found between radiocarpal joint intra-articular incongruity and outcome scores, as measured via the PRWE scale (Karnezis et al.). Obtaining proper anatomic reduction and restoring joint congruency have been positively linked to improved long-term functional outcomes post DRF treatment (Chung et al., 2007; McQueen, 1988; Solgaard, 1988; Trumble, Schmitt, & Vedder, 1994).

Loss of normal radial inclination angle leads to radial shortening and declined grip strength (Jenkins & Mintowt-Cryz, 1988). Radial shortening, produced also by dorsal angulation, and loss of normal radial inclination have been reported as the most common disabling deformities post DRF (Cooney, Dobyns, & Linscheid, 1980) as they disrupt the congruency of the radiocarpal joint and increase axial loading on the distal radioulnar joint (Adams, 1993; Pogue et al., 1990). Radial shortening of up to 5 mm is linked to a 20% grip strength deficit in DRF patients at 3-years post DRF (Villar, Marsh, Rushton, & Greatorex, 1987). Radial shortening of equal or greater than 6 mm is also associated with significant impairment of active forearm rotation (Zemel, 1987) as well as 35% grip strength deficit after DRF. Presence of radial shortening immediately post fracture or 1 week after treatment are the most significant correlates ($p < 0.001$)

of grip strength and wrist flexion active ROM after DRF (Villar et al.). Although grip strength is a significant predictor of PRWE functional scores amongst DRF patients (Karnezis & Fragkiadakis, 2002), no association has been found between radial shortening (up to 8 mm) either at injury or at fracture union and the PRWE functional scale (Barton et al., 2007).

Dorsal angulation of 10 to 45º may also cause significant radial shortening and altered wrist biomechanics due to redirection of axial forces being absorbed within the radiocarpal joint (Pogue et al., 1990; Short, Palmer, Werner, & Murphy, 1987). Axial force transmission through the ulnocarpal joint, which normaly is 20%, can increase up to 65% (Short et al.), resulting in greater loading and distortion of the triangular fibrocartilage complex due to decreased ulnar variance (Adams, 1993). Dorsal angulation is associated with loss of normal palmar tilt angle, leading to wrist ROM limitations (Kazuki, Kususnoki, Yamada, Yamada, & Shimazu, 1993) and promoting midcarpal joint instability (Taleisnik & Watson, 1984). This is particularly true when the dorsal angular deformity exceeds 20º as it disrupts normal inter-segmental carpal biomechanics (Park, Cooney, & Hahn, 2002).

Assessment of intra-articular congruity has become an important prognostic factor for future development of

post-traumatic osteoarthritis (Catalano, Cole, & Gelberman, 1997; Knirk & Jupiter, 1986; Pogue et al., 1990). Even a small step-off deformity of 1 mm has been linked to higher risks for developing long-term radiocarpal joint arthrosis (Bradway, Amadio, and Cooney, 1989; Knirk & Jupiter). However, the clinical meaningfulness of an intra-articular step-off deformity less than 3 mm is questionable due to its poor inter-rater reliability among physicians (Chung et al., 2007; Kreder, Hanel, & McKee, 1996). The incidence of post-traumatic osteoarthritis at the radiocarpal joint was reported to be 33% 10 years after a displaced (> 3 mm) intra-articular DRF (Field, Warwick, Bannister, & Gibson, 1992). Associated soft-tissue injury after intra-articular DRFs could be another contributing factor to radiocarpal and ulnocarpal joint instability and developing osteoarthritis. A 78 and 54% incidence of triangular fibrocartilage complex and scapholunate ligament tears respectively have been demonstrated after intra-articular DRFs (Richards, Bennett, Roth, & Milne, 1997).

A concomitant ulnar styloid fracture has also been considered for its effect on DRF functional outcome. Ulnar styloid fractures are typically assessed via posterior-anterior and lateral x-ray views (Souer et al., 2009). This fracture type coincides with 50 to 60% of

DRFs (Sammer, Shah, Shauver, & Chung, 2009; Zenke, Skai, Oshige, Moritani, & Nakamura, 2009), leading to potential instability at the distal radioulnar joint (May, Lawton, & Blazar, 2002). Determining whether the presence of an associated ulnar styloid fracture affects a patient's functional outcomes post DRF is controversial (Sammer et al.; Souer et al.). There is some evidence supporting the fact that displaced ulnar styloid base fractures cause distal radioulnar joint instability, leading to poor functional outcomes (Geissler, Fernandez, & Lamey, 1996; Lindau, Ablercreutz, & Aspenberg, 2000). However, recent evidence supports that distal radioulnar instability is infrequent (approximately 3%) post ulnar styloid fracture (Sammer et al., 2009) and both short- and long-term (12 months) objective outcomes, such as wrist active ROM, grip strength, pain, and functional score, do not differ significantly between patients with and without ulnar styloid fractures (Sammer et al.; Souer et al.; Zenke et al.). Similar results are reported when DRF patients are stratified on ulnar styloid fracture severity and displacement levels (Souer et al.). Only a small percentage (4.2%) of DRF patients with concomitant ulnar styloid fracture are found to sustain long-term ulnar-sided wrist, the primary reason of which is attributed to decreased ulnar variance (Zenke et al.).

International Classification of Functioning Model for Distal Radius Fractures

Universal Classification of Disease and Health

In 1980, the original International Classification of Impairments, Disabilities and Handicaps was published by the World Health Organization (WHO) with the intent of establishing a hierarchical order of the physical consequences that occur from a disease process (WHO, 1980). This hierarchical framework was based on the three domains of impairment, disability, and handicap, which were thought to be linearly associated (Barbotte, Guillemin, Chau, & Lorhandicap Group, 2001). As disease-specific impairment levels increased, disability and handicap levels of the same disease were expected to rise with comparable rates. Increased application of the original classification model led to greater understanding of previously ignored interactions among the three domains and other extrinsic relevant factors (i.e., environmental influences, social interactions, demographics, and psychological status), indicating that inter-domain associations behave in non-linear patterns under the influence of confounding extrinsic factors (Harris et al., 2005).

In 2002, as a consequence of evolving knowledge, WHO updated its original classification framework to a new International Classification of Functioning, Disability,

and Health (ICF) model (Cieza et al., 2002; WHO, 2002). The ICF model framework was structured around three new health-related domains of body structure and function, activity, and participation, reflecting current emerging health standards and demands (WHO) as well as not using insensitive terminology per the previously used labels of disability and handicap (Harris et al., 2005). The new theoretical priority of the ICF model was to emphasize human health and function rather than disability, which was previously thought to be a direct consequence of physical impairment and known to classify people in exclusionary societal categories (WHO).

The new ICF model shifted from a disease cause to a disease impact on society focus. This model is considered to offer a conceptual framework for classification and assessment of people’s health and functional levels in society, regardless of the source and level of their physical impairment. It integrates medical and social views of activity limitation, acknowledging that activity limitation is not an isolated experience among a minority population but rather a universal phenomenon that can occur to all humans after developing a health decrement. The ICF model regards disability as a synthesis of bio-psychosocial interactions among biological (e.g., diseases, injuries) and individual (e.g., gender, age, education) intrinsic factors and socio-environmental

extrinsic phenomena (e.g., social attitudes, architectural barriers, climate). The new ICF model offers a more versatile basis for assessing human health and function. It provides a broader spectrum of use in many health conditions, using a common metric language related to global human function and health. (WHO, 2002)

Comparing the new and old ICF model frameworks reflects the ideological differences between their three domains. The first domain of the new ICF model is body function and structure, previously known as impairment, and refers to deficits in anatomy or physiology (e.g., pain, loss of ROM, and strength), which can be individually measured via reliable objective testing (Grimby & Smedby, 2001; WHO, 2002). This domain reflects the medical view of disease or other health conditions and their required medical management provided by health professionals (WHO). The second domain of the new ICF model, previously known as disability, is now labeled activity (WHO) and it addresses activity limitations or difficulty performing tasks such as turning a handle, writing, and opening a jar (Grimby & Smedby; WHO). The third domain of the new ICF model, previously known as handicap, is now labeled participation (WHO) and it addresses participation restrictions such as difficulty engaging in roles (e.g., playing sports, gardening, babysitting, traveling) and activities (Grimby & Smedby;

WHO). Both the second and third domains reflect a more societal view of what previously was known as disability and handicap. They reject disability and handicap being individual attributes, describing them as being a result of unaccommodating social attitudes and environmental barriers (WHO). Objective assessment of functional limitations related to the second and third ICF domains is conducted via reliable outcome measures (Cieza et al., 2002).

The ICF is a health-related classification system with multiple applications in different sectors, which can be used internationally by health professionals as a scientific scale for consistent and comparable measurements about the experience of human health and disability. Having a very flexible, detailed, and complete framework as well as domains operationally defined with specific inclusion and exclusion criteria, the new ICF system is expected to advance clinical practice. Specifically, the ICF system can be used to classify a person’s level of function and to guide treatment planning towards those interventions that lead to maximum functional outcomes. (WHO, 2002)

The new ICF system is anticipated to have benefits at the institutional, social, and medical research levels. At the institutional level, it can be used in guiding health-care resource planning and development, as

well as evaluating health-care service quality and cost-effectiveness. At the social level, it can be used in the development of social policy and to reinforce insurance legislation and reimbursement related to eligibility criteria for social security and disability benefits. It is also expected to facilitate efforts for identifying accessibility barriers and guiding social policy towards making social environment accessible for all people regardless of their activity limitation level. In medical research, it can be a beneficial scientific assessment tool to classify and measure functional outcomes of various health conditions, using universal and interdisciplinary standards that focus on the whole human being (WHO, 2002).

Recent research has attempted to apply the ICF models into specific health conditions or injuries (Cieza et al., 2002; Escalante et al., 2005; Pap, Angst, Herren, Schwyzer, & Simmen, 2003; Tremayne et al., 2002) in an effort to better reflect all domains of patient physical impairment, activity limitations, and social or vocational participation status following a specific musculoskeletal disorder (Harris et al., 2005). Establishing compatible links between measures of functional outcomes and the ICF model is a vital step towards directing quality of care (Stucki, Ewert, &

Cieza, 2002) as well as providing a common language for clinical practice, teaching, and research (Cieza et al.).

Implementation on Distal Radius Fractures

The primary goal of rehabilitation following DRF interventions is to restore optimal function (Laseter & Carter, 1996), integrating all body functions, activities, and social participation patient needs (Tremayne et al., 2002). DRF rehabilitation should follow current clinical quality management standards (Dekkers & Soballe, 2004). These standards are driven by evidence-based principles, rely on valid and reliable health outcome measurements, require a greater focus on applying the ICF model towards determining functional outcomes, and apply across various health conditions (Cieza et al., 2002; Stucki et al., 2002).

Rehabilitation assessment after DRF should comply with ICF principles (Harris et al., 2005), requiring that reliable outcome measurements of health are applied in a holistic evidence-based evaluation approach as in any other musculoskeletal disease or surgery (Tremayne et al., 2002). Strong correlations have been reported between DRF patient functional outcomes and impairment levels post DRF. For example, scores of the Disability of the Arm, Shoulder and Hand (DASH) scale (Hudak, Amadio, Bombardier, & UECG, 1996), which is a self-reporting

functional outcome questionnaire, are highly correlated with wrist extension ($r = -0.50$, $p = 0.01$) and supination ($r = -0.47$, $p = 0.02$) ROMs (Lucado et al., 2008). Similarly, use of the PRWE scale, also a self-reporting measure for pain and function outcomes, is strongly associated with grip strength. Grip strength was determined to be a strong predictor ($R^2 = 0.43$, $p < 0.01$) of PRWE scores among DRF patients (Karnezis & Fragkiadakis, 2002). Assessment priorities post DRFs should not only be focused on the impairment level but also follow current clinical evidence, knowledge, and expertise (Harris et al.). It should also systematically integrate patient impairment with patient activity capacity, social participation, and personal values since it is reasonable to infer that impairments may exist without activity limitations or vice versa (Tremayne et al.).

No research has been published to date to compose a multi-dimensional DRF-specific ICF model that reflects the full clinical framework of impairments, activity limitations, and social participation barriers commonly evaluated following DRF. Understanding how the ICF model applies to this very common forearm fracture, known to have an impact on overall health, would assist all involved medical professionals in planning better treatments and directing more efficacious rehabilitation

methods towards ultimate functional outcomes post DRF (Tremayne et al., 2002).

Constructing a DRF-specific ICF model should first involve a physical function analysis, which encompasses all documented impairments that occur from DRF trauma as well as its immobilization or surgical management. Commonly reported impairments and co-morbidities following DRFs include wrist pain; edema; wrist ROM loss; and grip strength decrement (Handoll et al., 2006; MacDermid et al., 2002; Tremayne et al., 2002); declined hand dexterity (MacDermid et al.), finger stiffness; loss of sensation due to median, ulnar, or radial nerve compression neuropathies (Cooney et al., 1980; Dennison, 2006); reflex sympathetic dystrophy (Hove, 1995); radiocarpal or radio-ulnar arthrosis; tendon ruptures; forearm compartment syndrome; fracture malposition-malunion (Cooney et al.); and severity of fracture displacement (Stewart, Innes, & Burke, 1985b).

The domains of activity limitation and restricted social participation in a DRF-specific ICF model should encompass information deriving from functional outcome measures that are found to be reliable and responsive in evaluating DRFs recovery. Criteria on the development and formatting of wrist outcome measures that would become essential components for DRF clinical assessment and treatment have been established (MacDermid et al., 1998).

Based on these criteria, the most critical subjective factors for clinical usefulness were pain, functional ability, and patient satisfaction. The most important objective measures were functional tests, grip strength, and wrist ROM. Functional scales such as the DASH (Lucado et al., 2008), PRWE (MacDermid et al., 2000), and Short Form-36 (SF-36; McHorney, Ware, & Raczek, 1993) meet the aforementioned criteria, and are highly responsive to DRF patients, especially during the initial 0 to 3 months of treatment when full physical testing can not be performed. Using the standardized response mean (SRM) as an index of responsiveness, both the DASH (SRM = 2.01) and PRWE (SRM = 2.27) were found to be more responsive than the SF-36 (SRM = 0.92), with the PRWE being the most responsive, especially during the 3 to 6 months immediately post DRF (MacDermid et al.).

In a DRF-related ICF model, extrinsic factors can mediate or predict the outcomes addressed within the central core of its three intrinsic domains. DRF functional outcomes have been correlated with personal patient attributes such as age (Chung et al., 2007; MacDermid et al., 2002), income (Chung et al.), education level, and injury compensation status (MacDermid et al.). In addition, gender, and pre-injury bone mineral density levels are among the most documented risk factors associated with DRF (Kelsey et al., 1992; Lippuner et

al., 2009; Singer et al., 1998; Vogt et al., 2002). Other independent predicting factors for DRF are poor visual acuity and lack of frequent walking (Kelsey et al.). The ICF model regards activity limitations as a synthesis of multiple bio-psychosocial influences. Application of the ICF model to DRF should encompass all relevant factors and compatible links to the three intrinsic domains of its central core. All of the inter-relating components of the DRF ICF model should be illuminated and applied towards measuring people's levels of health and function in society as well as ensuring the quality of their clinical care.

Functional Outcomes

Although current DRF research has consistently reported clinical outcomes based on both impairment and functional outcome measures (Handoll et al., 2006), only a few reported research studies have attempted to apply the ICF model to the functional disablement process associated with this fracture. MacDermid et al. (2001) intergrated multiple patient factors and treatment outcome data towards the conseptualizaton of a DRF-specific ICF model. Their primary objective was to provide a continuoum of descriptive data on physical impairments as well as functional, social, and emotional disablement scores measured during the first year after a DRF. Their secondary objective was to determine whether

patient factors (e.g., age, gender) and baseline patient-reported functional scores shortly after treatment are strong predictors for long-term outcomes 12 months after a DRF. A cohort of 250 DRF patients was enrolled in an outcome evaluation process that consisted of patient-rated questionnaires (PRWE, DASH, and SF36), active wrist ROMs, and grip strength. Multiple demographic data were obtained (i,e., fracture classification, gender, age, hand dominance, injury mechanism, medical history, history of falling, education level, occupation, satisfaction with care, alcohol consumption). All DRF patients were assessed at their initial visit to physical therapy after treatment as well as 2, 3, 6, and 12 months after fracture.

Results of the MacDermid et al. (2001) study demonstrated a trend of a steady improvement for almost every outcome tested at all successive evaluation times until 6 months. This improvement leveled off between 6 and 12 months. The mental health component of the SF36 questionnaire was the only outcome that did not change overtime, indicating that a DRF has a minimal emotional effect on the patient’s quality of life or general health. Among the three questionnaires, PRWE scale was found to be the most sensitive to functional change over time after DRF. The DASH scale was found to be more sensitive to functional change than the SF36. All active

wrist ROMs improved to within functional levels at 6 months after fracture. Grip strength improved to approximately 77 and 83% of the unaffected side at 6 and 12 months after fracture, respectively. PRWE, DASH, and ROM scores were not affected by patient age or gender across all assessment times. Gender had an effect on grip strength. A multiple step-wise regression analysis prediction model indicated that baseline scores of the three used functional questionnaires can explain only up to 27% of the variations in the 12-month outcome scores. The inclusion of other patient factors (i.e., gender, age, injury compensation) did not have further predictive value.

The MacDermid et al. (2001) study results offer stable short- and long-term patient outcome estimates of physical impairment, activity limitation, and social disablement after DRF. This baseline information can be used by therapists to assess patient clinical progress or treatment prognosis over time. Clinicians should expect a gradual change in patient outcomes until 6 months after DRF. Only small non-clinically meaningful outcome changes are expected after 6 months of DRF recovery. Data from questionnaires play a vital role in evaluating patients during the initial 8 weeks of DRF recovery when certain (e.g., grip strength) impairments could not be measurable. Their baseline scores after DRF are important

predictors for patient long-term recovery outcomes. Although detailed demographic data were initially collected in various patient factors, only few of these patient factors (i.e., gender, age, injury compensation) were used for the final analysis of this study. This study limitation directly affected results of the step-wise regression analysis, which showed only a small to moderate level of final outcome predictability. Using a greater number of relevant patient factors in addition to the three questionnaires could have created an expanded regression model with a higher predictive ability for long-term outcomes after DRF.

Tremayne et al. (2002) investigated the short-term relationship between impairment level and activity limitation post DRF. A sample of 20 Australian DRF patients (11 females and 9 males), 20 to 80 years of age and treated conservatively via 6-weeks cast immobilization, were assessed after removal of their cast for wrist extension active ROM, grip strength, and functional performance on the Jebsen-Taylor Hand Function Test. The latter represents one of the oldest standardized tests of hand function, which was originaly developed for individuals with spinal cord injuries. This test is used to assess fine and gross motor hand function on seven timed activity subsets: writing a sentence, turning 5 cards, picking and placing in a tin

small objects (i.e., bottle tops, USA pennies, paper clips), simulating feeding, stacking checkers, as well as lifting five light (1 lb empty) and five heavy (1 lb full) baked bean tins on to a board. The scoring method is the time necessary to complete each subtest using a stop watch. The final score consists of the cumulative time needed for all tasks tested (Jebsen, Taylor, Trieschmann, Trotter & Howard, 1969).

Results of the Tremayne et al. (2002) study revealed moderate to strong correlations ($r = -0.51$ to -0.76, $p < 0.05$) between grip strength and all seven functional tasks of the Jebsen-Taylor Hand Function Test. In contrast, extension active ROM impairment was strongly correlated with the Jebsen-Taylor Hand Function Test item of lifting large, light objects. When only Colles' fracture sub-types were analyzed, extension active ROM impairment was correlated with two more activities: turning cards and simulating feeding. The latter becomes a meaningful finding only if the intended clinical objective is to assess DRF sub-types in isolation. Although a limitation of this study was the relatively small sample size, supporting evidence may be drawn for the use of grip strength and extension active ROM measurements towards determining hand function post DRF conservative treatment via 6-weeks cast immobilization. Another limitation of this study was the inadequacy of

the Jebsen-Taylor Hand Function Test to fully represent all ICF domains such as participation restriction or engaging in social roles.

Sears and Chung (2010) concluded that the Jebsen-Taylor Hand Function Test has poor validity and responsiveness when applied to surgically-treated hand patients, including those with DRFs. Poor correlation was revealed between the Jebsen-Taylor Hand Function Test scores and the Michigan Hand Outcomes Questionnaire test scores at 3 (ICC = -0.38) and 12 (ICC = -0.30) months post DRF surgery. In addition, its responsiveness to hand function after surgery was estimated to be low (SRM = 0.54) among post-surgical DRF patients. It was also concluded that the Jebsen-Taylor Hand Function Test does not relate well to patient satisfaction or patient perception of hand function after hand surgery. Because of these limitations, its use as a measure of hand function and disability should be discouraged (Sears & Chung). Accordingly, a critical methodological limitation for both aforementioned studies is the use of a non-validated functional test, which fails to assess patients on all the ICF domains such as participation restriction and engagement in social roles.

Dekkers and Soballe (2004) investigated short-term (5 weeks) functional limitations after extra-articular DRFs, which were treated with closed reduction and 6-

weeks cast immobilization. A sample of 33 Danish females 51 to 87 years of age was used. All patients started rehabilitation 2 to 3 days post cast removal. Once all relevant impairments (i.e., pain, active ROM, grip strength, manual dexterity) were identified and assessed, they were correlated to the Canadian Occupational Performance Measure (Cup, Scholte, Reimer, Thijssen, & Kuyk-Minis, 2003), which was used to identify functional problems in the domains of activity limitation and participation restriction.

The Canadian Occupational Performance Measure is a client-centered outcome measure designed for use by occupational therapists to determine functional performance deficits as perceived by the patient over time. This scale meets the professional guidelines of client-centered practice used by occupational therapists and the standards of the Canadian model on occupational performance. It is completed via a semi-structured interview in which patients are encouraged to identify problems in their self-care, productivity, or leisure activities. Patients rate their performance and satisfaction on selected activities that they need or are expected to do, but cannot do, or those in which they are not satisfied with their current performance. Activity rating is based on a 10-point scale with higher scores

reflecting better performance and satisfaction as perceived by the patient. (Cup et al., 2003)

The Canadian Occupational Performance Measure intra-tester reliability was determined to be high for both functional performance (ICC 0.89, $p < 0.001$) and patient self-satisfaction scores (ICC 0.88, $p < 0.001$) among stroke patients. Its discriminant validity was confirmed via correlating its patient-selected items and performance scores with items and scores on five other standardized functional measures (Barthel Index, Frenchay Activities Index, Stroke Adapted Sickness Impact Profile-30, Euroqol 5D, and Rankin Scale), which are frequently used to evaluate stroke services in the Netherlands. The low Spearman correlation values ($r = 0.10$ to 0.22, $p < 0.05$) confirmed the discriminant validity of the Canadian Occupational Performance Measure, which covers a much broader spectrum of daily activities in the areas of self-care, productivity, and leisure than the other five standardized functional measures that were used as comparison (Cup et al., 2003). The psychometric properties of the Canadian occupational performance measure have yet to be determined for DRF patients.

Results of the Dekkers and Soballe (2004) study indicated a significant decline in impairment level from week 1 to week 5 post cast immobilization. The influence of pain on activities had significantly increased ($p =$

0.003). Active ROM values were measured as a percentage of the non-fractured side. Significant active ROM improvements (5 to 18%, $p < 0.01$) were found at 5-weeks post immobilization. Average grip strength had improved by 4.6 kg/cm^2($p < 0.001$) during the same time interval. At the first week, dexterity deficit of 23% was measured as a percentage of the non-fractured side, which was completely normalized 5 weeks later ($p < 0.001$). The number of patient-selected performance problems as well as performance and satisfaction scores were also significantly lower ($p < 0.001$) at 5-weeks post cast immobilization. Low to moderate linear correlations ($r = 0.35$ to 45) between impairment improvements and functional performance improvements were found at 5-weeks post cast immobilization, which coincided with pain and poor grip strength still affecting functional performance. These results indicated that the lower impairment of pain, active ROM, grip strength, and manual dexterity post DRFs does not correlate well with patient performance improvements. Thus, the Canadian Occupational Performance Measure lacks assessment specificity towards patient functional performance post DRF and it should not be considered a valid assessment tool that meets the ICF clinical framework standards.

In a Canadian prospective cohort study (Harris et al., 2005), 790 DRF patients, 18 to 91 years of age, were

assessed at 1-week, 3-months, and 1-year post injury via use of the PRWE and SF-36 to measure impairment, activity, participation, and health. The Wrist Outcome Measure (WOM), which is an impairment scale that is used to compositely measure ROM, grip strength, and dexterity, was also used but only at 3-months and 1-year post injury. This study's primary purpose was to determine whether the ICF framework served as an explanatory model for DRF and the impact of impairment, activity limitation, and participation restriction on physical and mental health after DRF.

Results of the Harris et al. (2005) study determined clear explanatory models of health outcome post DRFs as regression analysis showed that the PRWE scale explained 13 (one week), 33 (three months), and 28% (12 months) of the SF-36 physical health measures score variance. In this regression analysis age and gender, known to be influential factors on health, were statistically controlled. The PRWE scale demonstrated the greatest change on outcome measures scores across all assessment times. All PRWE subsections were weakly correlated ($r = -0.10$ to -0.34, $p = 0.01$) to the SF-36 mental component scores, but moderately correlated ($r = -0.27$ to -0.52, $p = 0.01$) to the SF-36 physical health scores. The PRWE subsection of usual activity demonstrated its strongest correlation ($r = -0.42$, $p = 0.01$) with the SF-36 physical

health measures at 3 months post injury as compared to its specific activity subsection, which showed its strongest correlation (r = -0.52, p = 0.01) with the SF-36 scale at 12 months. Wrist impairment scores derived from the WOM scale were found to be less powerful predictors of health status than the total PRWE score. Univariate analysis showed that all three scales (PRWE, SF-36, and WOW) were moderately correlated (r = 0.32 to 0.52, p = 0.01) among each other at 12 months after injury.

Harris et al. (2005) study results showed that there was improvements of all outcome measure mean scores across all assessment times. The high level of activity limitations and participation restrictions at week 1 improved to only a mild level of functional deficits perceived at 1-year post injury. Impairment, activity limitations and participation restrictions, individually or in combination, were correlated with self-reported functional outcomes (e.g., SF-36). It was concluded that DRF has a clear and measurable impact on functional and social participation and physical health status that follows a pattern compatible with the IFC framework model. Results of the Harris et al. (2005) study provide evidence to support the use of the SF-36 and PRWE scales in assessing DRF impact on patients' physical health and functional status. All aforementioned studies were

limited to only research strategies that linked the ICF model and DRF via studying isolated correlations between impairments and functional outcomes following DRF. Further research is needed to construct a comprehensive multi-dimensional DRF-specific ICF model that incorporates the full ICF clinical framework.

Distal Radius Fracture Physical Therapy Assessment

The population of older healthy and active adults has been steadily increasing over the past few decades (Ring & Jupiter, 2005). This age expectancy increase is concurrent with a 21 and 52% increase of DRF incidence rate for women and men, respectively (Melton, Amadio, Crowson, & O'Fallon, 1998). As a consequence, the negative impact of DRFs on a greater number of older adults' health has been rising, leading to greater importance of rehabilitation intervention with the primary objective of restoring optimal function (Jette, 1993; Laseter and Carter, 1996). Restoring optimal upper extremity function implies consideration of the physical body function, activity, and social participation components of the ICF (WHO, 2002). DRF patients are frequently referred for physical therapy following a period of immobilization or surgery (Wakefield & McQueen, 2000; Handoll et al., 2006). Optimally, physical therapy assessment following DRF should include measuring both

impairments and self-reported functional outcomes (Kotsis, Lau, & Chung, 2007) with responsive, clinically meaningful, and reliable objective measures (MacDermid et al., 2000).

Responsiveness of Outcome Measures Following Distal Radius Fractures

Clinimetrical sound instruments are essential for accurately measuring patient-health outcomes and assessing treatment efficacy based on clinical relevant improvements following therapeutic interventions (De Vet, Terwee & Bouter, 2003; De Morton, Davidson & Keating, 2010). Critical decisions on patient progression following DRF interventions are heavily dependent on clinically meaningful results derived from responsive measures (MacDermid, et al., 2000).

Determination of an instrument's responsiveness is critical for interpreting its clinical value in today's evidence-based medicine environment (De Morton et al., 2010). Instrument responsiveness is defined as its ability to accurately detect change (e.g., change of sensori-motor function) that has occurred within its specific clinical domain (Guyatt et al., 1987; Wright & Young, 1998; Beaton et al., 2001; Lehman & Velozo, 2010) and is considered an important component of instrument validity (Kirshner & Guyatt, 1985). The two statistical

methods that have been proposed as the gold standards for determining and reporting an instrument's responsiveness to change are: distribution- and anchor-based statistics (Juniper, 1998; Hurst & Bolton, 2004; Lehman & Velozo).

Distribution-based responsiveness indices.

Distribution-based methods consist of both group- and individual-based indices that intend to evaluate clinical outcome change at the level of statistical significance (Kirshner & Guyatt, 1985; Lehman & Velozo, 2010). Although current body of research agrees that distribution-based responsiveness represents a statistical estimate of an instrument's sensitivity to detect clinical change (Beaton et al., 2001) its interpretability has been controversial on whether it truly reflects a clinically meaningful change (Katz, Larson, Phillips, Fossel, & Liang, 1992; Guyatt, Kirshner, & Jaeschke, 1992; Hays, Anderson, & Revicki, 1993; Jenkinson, 1995; Wright & Young, 1998; Beaton, et al.). Among several group-based statistical indices that have been proposed as the gold standards for estimating an instrument's responsiveness, the ES and SRM are the two most commonly reported thresholds that intend to estimate health status clinical change between two or more assessment points in time (i.e., pre- and post-tests; Lehman & Velozo). In contrast, the MDC is an individual-based statistical index, which intends to

measure statistically significant health status change within a single patient two or more assessment points in time (Stratford et al., 1996; Schmitt & Di Fabio, 2004; De Morton et al. 2010; Lehman & Velozo).

Effect size.

Among all the aforementioned indices ES is the oldest responsiveness index and is defined as the magnitude of the mean score change divided by the initial scores standard deviation (Portney & Watkins, 1993). ES was first introduced by Cohen (1977) as the benchmark standardized index for determining statistical power. Its importance as a statistical analysis tool in interpreting health status change measures was first introduced by Kazis (1989) who conducted clinical research related to arthritis and other chronic disease. Recent research has reported ES as a statistical index for measuring outcome measures responsiveness to health status change following DRF and is interpreted as follows: .20 to .49 small, .50 to .79 moderate, and ≥ .80 large effects (Portney & Watkins; Cohen, 1998; Lehman & Velozo, 2010).

MacDermid et al. (2000) determined that the PRWE questionnaire is more responsive (ES = 3.16 to 3.91) than the DASH (ES = 1.86 to 2.32) and of the SF36 (ES = 0.90 to 1.27) during the 0- to 3- and 0- to 6-month periods following non-surgical and surgical DRF intervention. In the same study, high responsiveness for wrist active ROM

(ES = 0.67) and grip strength (ES = 0.84) measures were reported during the 0 to 6-month period after injury. Schmitt and Di Fabio (2004) determined high instrument responsiveness for both the DASH (ES = 1.87) and PRWE (ES = 1.87) questionnaires respectively among patients with distal upper extremity pathology, including DRF patients during the first 3 months after their initial visit in physical therapy.

Standardized response means.

SRM is a group-based responsiveness index, which is defined as an outcome's mean score change divided by the standard deviation of the score change (MacDermid et al., 2000) when a single baseline score measurement is used to assess health status change before and after treatment (Lehman & Velozo, 2010). Although both ES and SRM can comparably measure health status change, the SRM is considered to be a superior statistical coefficient for instrument responsiveness because it is not affected by sample size (Stratford, Binkley & Riddle, 1996). SRM, which is a variation of ES, was first introduced by Liang, Fossel and Larson (1990) who modified the original Cohen's (1977) ES formula denominator (i.e., standard deviation of initial scores) into the standard deviation of the score difference between assessment times (i.e., pre- and post-treatment). SRM index interpretation is based on the same scale as ES and it has been used as a

statistical threshold to determine instrument responsiveness in various clinical outcomes studies related to shoulder (Beaton, Katz et al., 2001; Gabel, Michener, Burkett & Neller, 2006; Chapman et al., 2008) and elbow (Newcomer, Martinez-Silvestrini, Schaefer, Gay & Arendt, 2005; Rompe, Overend & MacDermid, 2007) injuries.

There is a limited body of literature that reports SRM as an index for outcome measure responsiveness following DRF. MacDermid et al. (2000) determined that the PRWE questionnaire is more responsive (SRM = 2.27 to 2.95) than the DASH (SRM = 2.01 to 2.52) and the SF36 (SRM = 0.92 to 1.26) during the 0- to 3- and 0- to 6-month periods following non-surgical and surgical DRF intervention. In the same study, high responsiveness for wrist active ROM (SRM = 0.84) and grip strength (SRM = 1.52) measures were reported during the 0 to 6-month period after injury. Beaton, Katz et al. (2001) determined the responsiveness of the DASH questionnaire to be high among wrist and hand patient population including DRFs (SRM = 0.74 to 0.91). Schmitt and Di Fabio (2004) determined high instrument responsiveness for both the DASH (SRM = 1.67) and PRWE (SRM = 1.94) questionnaires respectively among patients with distal upper extremity pathology including DRF during the first 3 months after their initial visit in physical therapy.

The application of ES and SRM statistical indices in determining the active wrist JPS test responsiveness among patients following non-surgical and surgical DRF interventions has yet to be reported.

Minimal detectable change.

The MDC, also known as the smallest real difference, is an individual-based statistical index, which intends to measure the smallest statistically significant detectable health outcome change of an individual over time given the instrument of interest measurement error (Stratford, Binkley & Riddle, 1996; Schmitt & Di Fabio, 2004; Lehman & Vaelozo, 2010, De Morton et al., 2010). That is the level of individual score change, which is observed before the boundaries of measurement error allowing to identify real observed statistical change (King, 2011). The MDC value is determined via the formula: $MDC = z * SEM * \sqrt{2}$, where SEM is the standard error of measurement and a z score usually reflects a 90 to 95% confidence level (Lehman & Velozo). The advantage of the MDC formula is that it incorporates SEM, which reflects the amount of variance or error associated with an individual's repeated performance on the intended measured outcome (Stratford et al.). The other advantage of using the MDC approach is that it incorporates reliability (i.e., SEM) to assess an instrument's responsiveness. A lower reliability coefficient is

associated with a greater SEM value and therefore a higher MDC score. Greater instrument reliability is needed for determining outcomes measures responsiveness via individual- (i.e., MDC method) rather than group-based statistical indices (Schmitt & Di Fabio).

The MDC approach was first introduced by Stratford, Binkley, Solomon et al. (1996) who determined the minimum level of detectable change via the Roland-Morris Questionnaire among patients with low back pain following 6 weeks of physical therapy treatment. There is a limited body of clinical research that incorporates the MDC statistical index in determining responsiveness of outcome measures related to upper extremity injury, especially following DRF. Beaton, Katz, et al. (2001) determined the MDC value (CI = 95%) of the DASH questionnaire to be 12.75% in a prospective cohort of 172 patients 12 weeks following treatment for shoulder, wrist and hand injuries. Schmitt and Di Fabio (2004) determined the MDC value (CI = 90%) of the PRWE questionnaire to be 12.2% in a prospective cohort of 52 patients 12 weeks following distal upper extremity injury that included DRF. Gabel et al., (2006) determined the MDC value (CI = 95%) of the Upper Limp Functional Index questionnaire to be 10.4% in a prospective cohort of 130 patients 8 weeks following treatment for various diagnoses related to upper extremity that excluded DRF. The MDC value for the

active wrist JPS test among patients following non-surgical and surgical DRF interventions has yet to be determined.

Anchor-based responsiveness.

Anchor-based statistical method intends to estimate an instrument's responsiveness to outcome change at the level of clinical meaningfulness (Juniper, 1998; Lehman & Velozo, 2010; King, 2011). It consists of estimating a measure's MCID value, which represents the smallest clinically significant health status change (Jaeschke et al., 1989; Juniper; Lehman & Velozo). The MCID is usually larger than the MDC value (King) and it is estimated via anchoring a health outcome instrument with a global rating of change scale (e.g., PGIC scale), which serves as an external criterion and categorizes an individual's perceived level of disability change on a likert scale (e.g., worse or not better, mildly better, better, greatly better; Jaeschke et al.; Juniper et al., 1994; Schmitt & De Fabio, 2004; Farrar et al., 2001; Hurst & Bolton, 2004). A priory definition of an MCID value is used to set the global rating of change scale cutoff values that indicate clinically significant change. This is typically based on sensitivity and specificity statistical analyses of the intended global rating of change scale, which items are used to categorize

individual patients as improved or not improved (Hurst & Bolton). The true advantage of the MCID approach over other distribution-based statistical approaches (i.e., ER and SRM) is its ability to incorporate a patient's own impression of clinical change over time (Juniper et al.; Hurst & Bolton; Lehman & Velozo).

This statistical threshold was first introduced by Jaeschke et al. (1989) who determined the Chronic Respiratory Questionnaire and Chronic Heart Failure Questionnaire MCID values in measuring dyspnea, fatigue, emotional function and the effect of inhaled medications in a cohort of 31 patients with chronic lung disease who participated in a 24-week long respiratory rehabilitation program. Chronic Respiratory Questionnaire and Chronic Heart Failure Questionnaire were used as the primary measures, which were anchored to a PGIC scale. Patients were asked to make global ratings of their respiratory status, fatigue levels, and emotional status during their daily activities on a 15-point global scale, which was consisted of 7 response options if patients were worse (i.e., from great deal worse to almost the same), one selection for no change, and 7 response options if patients felt improved (i.e., great deal better to almost the same). The relationships between global rating of change and change in the primary measures were analyzed to

determine their corresponding MCID value, which was approximately 0.5 of within-subject score change. Similar methodology with the same PGIC scale was used by Juniper et al., (1994) to determine the MCID value of the Asthma Quality of Life Questionnaire in a cohort of 39 asthma patients who were assessed every 4 weeks during a 12-week rehabilitation period. They concluded that using this global rating scale a within-subject change in score of 0.5 represents the MCID value for the Asthma Quality of Life Questionnaire.

Farrar et al. (2001) conducted a retrospective study on data collected from 10 clinical trials with similar design (i.e., double-blind, multi-center, placebo-controlled) to determine the MCID value of the 11-point pain intensity numerical rating scale (i.e., 0 = no pain, and 10 = worst possible pain), which is frequently used to evaluate pain in today's clinical settings. They reviewed data from a total of 2724 patients of different age groups (range of 18 to 70) recruited with chronic pain (i.e., diabetic neuropathy, chronic low back pain, fibromyalgia, and osteoarthritis). Patients kept a daily pain diary for 7 days prior to taking medication and 7 days while receiving medication treatment. The baseline score consisted of the mean pain score value of the 7-day pre-treatment period. The endpoint was the mean pain

score value of the 7-day treatment period. They anchored the pain numerical rating scale scores to a 7-point PGIC scale, which consisted of 3 response options if patients were worse (i.e., very much worse, much worse, minimally worse), one selection for no change, and 3 response options if patients felt improved (i.e., very much improved, much improved, minimally improved). A priory definition of MCID was set to be the ‘much improved’ or better PGIC categories. Results of this study concluded that the 11-point pain intensity numerical rating scale MCID value is correlated with a reduction of approximately 2 or more points of pain intensity.

Hurst and Bolton (2004) conducted a prospective study on 265 consecutive patients who received chiropractic treatment for low back and neck pain to determine their MCID values on the Bournemouth Questionnaire pre- and post-treatment, which consisted of 4 visits within a 2-week period. Bournemouth Questionnaire was anchored to a 7-point PGIC scale, which consisted of one selection for being worse or no change and 6 response options for patient improvement (i.e., almost the same, a little better, somewhat better, moderately better, better and a great deal better). The main question of the PGIC scale was stated as follows: “Since beginning treatment at this clinic,

how would you describe the change (if any) in activity limitations, symptoms, emotions and overall quality of life, related to your painful condition?" The priory definition of MCID was "better" or greater on the PGIC scale. This was based on sensitivity and specificity analysis of the PGIC scale items, which categorized individual patients as improved or not improved. The best balance between high sensitivity and specificity was found on the PGIC cutoff values of ≥ 6 (i.e., better or great deal better), which correlated with MCID values of 47 and 34% on the BQ for back and neck patients, respectively.

Schmitt and Di Fabio (2004) conducted a prospective cohort study to determine the MCID values of the DASH and PRWE questionnaires on 155 patients (18 years and older) following various proximal and distal (including DRF) musculoskeletal upper extremity injuries, respectively. All patients were assessed at the initial physical therapy visit and 3 months later. The PGIC scale consisted of a similar 7-point global rating scale to the one used in the Hurst and Bolton (2004) with a modification of its main question, which was stated as follows: "how much has this problem affected your normal daily activities using your arm(s) during the past week?" Its 7 items were expressed from "no change or worse" to "great deal better" and were assigned a 1 through 7 score

values. A priory definition of MCID was a change of score of 1 or more on the PGIC scale to delineate the patients who had a clinical meaningful change from those who did not improved over the 3-month interval. Results of this study indicated that the MCID values for the DASH and PRWE questionnaires among patients with distal upper extremity injury are 17 and 24 points, respectively. Use of the MCID statistical threshold for determining the responsiveness of the active wrist JPS test among patients following non-surgical and surgical DRF interventions has yet to be reported.

Physical Therapy Assessment Components

Various documented impairments are measured in physical therapy following DRF. These impairments include pain; edema; loss of wrist ROM and grip strength (Handoll et a., 2006; MacDermid et al., 2002; Tremayne et al., 2002); declined hand dexterity (MacDermid et al., 2002); finger stiffness; loss of sensation due to median, ulnar, or radial nerve compression neuropathies (Cooney et al., 1980); and decreased proprioception (Karagiannopoulos et al., 2013). Assessing impairments and measuring outcomes allows clinicians to monitor the patient’s progress and set treatment goals (Taylor & Bennell, 1994; Watt, Taylor & Baskus, 2000).

Among the aforementioned impairments, active ROM and grip strength are the two most frequently documented clinical objective physical measures assessed after DRFs (Karnezis & Fragkiadakis, 2002). A common and reasonable inference by clinicians is that the severity level of these measurements directly reflects the patient's activity limitations or participation restrictions (Tremayne et al., 2002). Clinically significant correlations have been reported between impairments in wrist active ROM (MacDermid et al., 2002; Tremayne et al.) and grip strength (Karnezis & Fragkiadakis; MacDermid et al.) with patient functional status post DRF.

Range of motion assessment.

Measuring ROM impairments post DRFs typically include assessing active wrist flexion and extension, ulnar and radial deviation, and forearm rotation. A standardized goniometry protocol is recommended for clinicians to assess wrist active ROMs (Horger, 1990). Wrist extension and flexion are best measured via volar and dorsal approaches, respectively. The volar approach consists of the movable and stationary goniometer arms being placed over the palm in alignment with the third metacarpal and along the volar surface of the distal forearm, respectively. The axis of the goniometer is aligned with the volar wrist surface. The dorsal approach

consists of the movable and stationary goniometer arms being placed over the dorsal surface of the third metacarpal and along the dorsal surface of the distal forearm, respectively. The axis of the goniometer is aligned with the dorsal carpus (LaStayo & Wheeler, 1994). Taking the average of two measurements results in high intra-rater reliability of wrist flexion and extension active ROMs (ICC = 0.95 to 0.96) and is typically used as the final assessment value (Horgen).

Both wrist ulnar and radial deviation active ROMs are measured with the goiniometer placed over the dorsal wrist. The goniometer's movable arm is aligned parallel to the longitudinal axis of the third metacarpal, the stationary arm is aligned along the midline of the distal forearm, and the axis is placed over the capitate bone (Clarkson & Gilewich, 1989). Taking the average of two measurements results in high intra-rater reliability of wrist ulnar and radial active ROMs (ICC = 0.90 to 0.92) and is typically used as the final assessment value (Horgen, 1990).

Functional supination and pronation active ROMs are measured via the hand-held pencil technique. In this technique the arm is fully adducted, elbow is flexed to 90°, and the forearm is in a neutral position (i.e., horizontal to the floor with palm facing medially;

Clarkson & Gilewich, 1989). The patient holds in a tight full fist a 15 cm long pencil, which extends from the radial aspect of the patient's hand. After the patient rotates his/her forearm, maximum active pronation or supination ROM is measured by aproximating the axis of the goniometer with the head of the third metacarpal, placing the stationary arm perpendicular to the floor, and aligning the movement arm parallel to the pencil. Taking the average of two measurements results in high intra-rater reliability of functional supination and pronation ROMs (ICC = 0.95 to 0.98) and is used as the final assessment value (Karagiannopoulos, Sitler, & Michlovitz, 2001).

Normal average wrist active ROM in flexion is 73 to 76°, in extension is 71 to 75°, in radial deviation is 19 to 21°, in ulnar deviation is 33 to 36°, in pronation is 71 to 75°, and in supination is 82 to 84° (American Academy of Orthopaedic Surgeons, 1965; Boone & Azen, 1979). Brumfield and Champoux (1984) first determined that most activities of daily living require an optimum wrist active ROM of 10° in flexion and 35° in extension. Palmer, Werner, Murphy, and Glisson (1985) reported that most activities of daily living required active ROMs of 30° extension, 5° flexion, 10° radial deviation, and 15° ulnar deviation. Ryu, Cooney, Askew, An, and Chao, (1991) reported wrist active ROMs to be functional at 40° for

both flexion and extension and 40° for combined ulnar and radial deviations. Functional active forearm rotation was determined by Morrey, Askew, and Chao, (1981) to be 50° for both pronation and supination.

The intra- and inter-rater reliabilities for wrist extension have been determined to be high (ICC = 0.84) for the volar measurement method. The intra- and inter-rater reliabilities for wrist flexion have been determined to be high (ICCs = 0.93 and 0.92) for the dorsal measurement method (LaStayo & Wheeler, 1994). Intra- and inter-rater reliabilities for ulnar (ICCs = 0.90 and 0.86) and radial (ICCs = 0.92 and 0.78) deviation have been determined to be high for both methods (Horger, 1990). Intra- and inter-rater reliabilities for functional supination (ICCs = 0.98 and 0.96) and pronation (ICCs = 0.97 and 0.95) have been determined to be high among wrist trauma patients (Karagiannopoulos et al., 2001).

Grip strength assessment.

Mathiowetz, Weber, Volland, and Kashman, (1984) and Kennedy, Jerosch-Herld, and Hickson, (2010) described a standardized protocol for grip strength measurement via a hand-held Jamar dynamometer. Patients are tested in a seated position with feet flat on the floor, shoulder in neutral adduction and rotation, the elbow flexed to 90°, and the forearm and wrist in neutral positions. Taking

the average of three measurements at both sides, alternating between the unaffected and affected sides, has been the gold standard method for assessing maximum grip strength. The intra- and inter-rater reliabilities of this measurement were reported to be high among healthy adults (ICC = 0.89 to 0.94; Mathiowetz et al., 1984). Similarly, high (ICC = 0.87 to 0.96) inter-rater reliability of grip strength assessment has been reported among patients with cumulative hand trauma (MacDermid, Kramer, Woodbury, McFarlane, & Roth, 1994).

A recent study by Kennedy et al. (2010) determined that assessing grip strength via 1 trial is equally reliable (intra- and inter-tester ICCs = 0.92 to 0.96) to the 3-trial assessment method amongst patients with rheumatoid arthritis. Thus, one-trial grip assessment amongst patients could save valuable clinical time and reduce the burden of pain associated with multiple grip trials. When grip strength is measured with repeated trials, a 1-minute recovery time is recommended between trials to fully account for fatigue effects (Kennedy et al., 2010).

Functional outcome measures.

Impairments seen after DRF are multidimensional and only partially captured by physical measures (Amadio, Silverstain, Ilstrup, Schleck, & Jensen, 1996). Clinically useful information regarding the patient’s

functional capability after DRF needs to be derived from valid and reliable patient-rating scales (Kotsis et al., 2007). Such scales need to provide a mechanism to capture both the functional limitations and physical impairment dimensions objectively (Amadio et al.), complying with ICF model principles (Harris et al., 2005).

Gartland and Werley (1951) proposed the first method for evaluating functional outcome post DRF, using a list of both objective and subjective criteria. In their study they recruited 60 DRF cases, which were all treated conservatively with below-elbow cast-immobilization for 6 weeks. All of their DRF were classified into 3 grades (non-articular, comminuted and non-articular, comminuted and articular), and their outcome was assessed at 18-months post fracture, using a point system. This multifactorial outcome measure tool assessed DRF patients on radiological findings, subjective reports, active ROM values, and fracture complications.

Radiological evidence was used to evaluate the presence of residual osseous wrist deformities on a 0- to 3-point scale. This scale was interpreted as follows: 0 for no bony deformity, 1 for prominent ulnar styloid, 2 for radius dorsal tilt, and 3 for both radius dorsal tilt and radial deviation of the hand. Patient subjective reports (i.e., pain, motion limitation, and activity restriction) were evaluated on a 0- to 6-point scale as

follows: 0 for excellent outcome with pain free status, and no disability or motion limitation; 2 for good outcome with occasional pain, slight motion limitation, and no disability; 4 for fair outcome with occasional pain, some motion and strength limitation, and slight disability; and 6 for poor outcome with significant pain, motion, strength, and disability limitations.(Gartland & Werley, 1951)

Both active ROM loss and post-fracture complications were graded on a 1- to 5-point scale. The active ROM loss scale was interpreted as follows: 1 for loss of either flexion or radial deviation, 2 for loss of supination, 3 for loss of ulnar deviation, and 5 for loss of extension. The 1- to 5-point post-fracture complication scale was based on increasing arthritis severety in the radio-carpal joint. Increasing severity of median nerve injury and finger stiffness complications were graded in a 1- to 3-point scale. A final composite point score was used to objectively categorize DRF patients into an excellent, good, fair, or poor recovery level. (Gartland & Werley, 1951)

Results of the Gartland and Werley (1951) study indicated that the patient’s final composite point score was positively associated with their original DRF classification. Most patients with higher scores were

found to have comminuted and intra-articular DRFs. No statistical data were reported to substantiate this proposed correlation between final patient score and fracture classifications. The Gartland and Werley DRF outcome scale has been used in numerous clinical studies (Davis & Buchanan, 1987; Ledingham et al., 1991; McAuliffe et al., 1987; Moir et al., 1995; Rosenthal & Blazar, 2006; Rush & Papadonikolakis, 2006; Stewart, Innes & Burke, 1984; Tumia et al., 2001; Young, Nanu & Checketts, 2003). Although it was originally introduced by Gartland and Werley as a functional scale, its intrinsic structure heavily contradicts this assertion. The focus of this scale is mainly on assessing physical impairments seen post DRF. It did not address patient activity and social participation limitations. Despite its popularity among physicians, it still remains a non-validated outcome instrument with its psychometric properties, including its MDC and MCID values, yet to be determined (Handoll & Madhok, 2003a).

Currently, various other functional outcome assessment tools have been developed and utilized to assess the impact of injury and treatment progression from the patient’s perspective after DRF. These outcome tools are likely to be more responsive and valid as they are characterized by their degree of body function or region specificity (Kotsis et al., 2007). They include

global health and quality of life measures, such as the SF-36 health survey (McHorney, 1993); regional specific measures, such as the DASH scale (Hudak et al., 1996); and more tissue-specific (e.g., wrist and hand), such as the Jebsen-Taylor Hand Function Test (Jebsen et al., 1969), PRWE (MacDermid, 1996), and Michigan Hand Outcome Questionnaire (Kotsis et al., 2007; Chung, Pillsbury, Walters, Hayward, & Arbor 1998).

Global-health outcomes.

Although the SF-36 health survey has been demonstrated to be clinically meaningful for assessing a variety of physical health and mental conditions (Ware & Sherbourne, 1992), it has been criticized for lacking specificity and being too long for patient health measurement efforts. It is strongly correlated ($r = 0.91$) with the 12-item shorter version SF-12 scale, which has high test-retest reliability (ICC range 0.89 to 0.76) and is a quicker option for patient physical and mental health assessments (Ware, Kosinski, & Keller, 1996).

The MCID for the SF-36 health survey has been determined by Angst, Aeschlimann, and Stucki (2001) for patients with knee and hip osteoarthritis at 3 months following a 4-week rehabilitation program. They determined MCIDs of 7.8, 3.3, and 2.0 for the SF-36 health survey bodily pain, physical function, and physical component subsections, respectively. The SF-36

health survey psychometric properties, including the MCD and MCID values, have yet to be determined for DRF patients. However, the SF-12 health survey MDC and MCID values have been determined by Schmitt and Di Fabio (2004) for patients with distal upper extremity musculoskeletal injuries, including DRF, to be 8.2 and 7.3, respectively.

Regional outcomes.

The DASH questionnaire is a 30-item functional scale that is used to measure function, symptoms, and quality of life status following upper extremity pathology (Hudak et al., 1996; MacDermid et al., 2000). It contains questions that reflect three dimensions of human function: physical, social, and psychological. Symptom questions relate to pain, weakness, tingling, numbness, and stiffness (Hudak et al.). Each question is scored on a 5-point Likert scale format, and its total score is based on a percentage out of 100%, with higher scores indicating greater disability (MacDermid et al.). Beaton, Katz, et al. (2001) determined the MDC value (CI = 95%) of the DASH questionnaire to be 12.75%. Schmitt and Di Fabio (2004) determined the MCID value for the DASH questionnaires to be 17% points.

Tissue-specific outcomes.

The Jebsen-Taylor Hand Function Test is used to evaluate fine and gross motor hand function. This test

consists of seven timed activity subsets: writing a sentence, turning cards, moving small objects, simulating feeding, stacking checkers, as well as lifting light and heavy objects (Jebsen et al., 1969). It has moderate to high intra- and inter-tester reliabilities for measuring hand function among patients with a hand disability (ICC range 0.60 to 0.99; Jebsen et al.) and older adults (ICC 0.82; Hackel et al., 1992). However, it has been determined to have poor validity, based on correlation with the Michigan Hand Outcome Questionnaire (r = -0.38 to -0.30), and low to moderate responsiveness to hand function (SRM = 0.54) when applied to surgically treated hand patients, including those with DRF. In addition, the Jebsen-Taylor Hand Function test does not relate well to patient satisfaction or perception of hand function after hand surgery. Accordingly, its use as a measure of hand function and disability has been discouraged (Sears & Chung, 2010). Its MDC and MCID values have yet to be determined for patients following DRF.

The PRWE is a 15-item questionnaire that is used to rate wrist and hand outcomes on pain, as well as specific and usual patient functions (MacDermid et al., 2000). Pain is measured on a 5-item sub-scale under both resting and functional activity conditions. Its 6-item specific activity sub-section is used to assess specific functional tasks, such as turning a door knob, cutting

with a knife, fastening buttons, pushing off a chair, carrying 10 pounds of weight, and using bathroom tissue. Its 4-item usual function sub-section is used to assess social participation roles associated with everyday work, personal care activity, recreational, and household activities (MacDermid, 1996). Each sub-section of the PRWE can be scored separately as well as a composite instrument score can be obtained. The composite score is based on a percentage out of 100%, with higher scores indicating increasing level of disability (MacDermid et al.).

All three PRWE sub-scales have been determined to be highly reliable among wrist-injured patients (ICCs range 0.89 to 0.90), including DRF patients (MacDermid et al., 1998). The PRWE construct and criterion validities have been established via statistically significant correlations ($p < 0.0001$) with the SF-36 questionnaire (MacDermid et al., 1998). Both the DASH (SRM = 2.52) and PRWE (SRM = 2.95) functional scales were found to be more responsive than the SF-36 (SRM = 1.29), with the PRWE to be the most responsive up to 6 months post DRF (MacDermid et al., 2000). Schmitt and Di Fabio (2004) determined the MDC (CI = 90%) and the MCID values of the PRWE questionnaire to be 12.2 and 24% points, respectively.

The Michigan Hand Outcome Questionnaire is a 57-item hand specific questionnaire that is used to assess

patients in six domains: overall function, activities of daily living, pain, work performance, aesthetics, and patient satisfaction. All domains except work performance assess function in each hand independently. Each domain is scored based on a 0 to 100% scale with 100% representing normal functional status (Chung et al., 1998). Test-retest reliability has been determined to be high for all of its domains (ICC range 0.86 to 0.97) among patients with hand disorders. High correlation of the Michigan Hand Outcome with the Short-Form 12 scale (r = 0.54 to 0.79) provided evidence for its construct validity, based on the assumption that both scales have similar structures to assess pain, work performance, and activities of daily living (Chung et al.). The Michigan Hand Outcome responsiveness has been determined (SRM range 0.2 to 1.0 for each domain) specifically for only surgically treated DRF patients (Kotsis et al., 2007).

Shauver and Chung (2009) reported the single study that has attempted to determine the Michigan Hand Outcome MCID value for post-surgical carpal tunnel syndrome and DRF patient populations. They reported MCIDs of 23, 8, and 13% points for the pain, work, and functional activities individual Michigan Hand Outcome scale domains 9 months following carpal tunner release. Determination of an MCID value for their DRF population was not possible. The Michigan Hand Outcome domains failed to

show adequate discriminative ability between 3 and 12 months following DRF surgery. They attributed this discrepancy to a study design limitation. Their DRF surgical population had already reached high functional recovery at 3 months, creating a ceiling effect that prevented significant reported function change at 12 months. The MDC value for the Michigan Hand Outcome Questionnaire has yet to be determined for patients following DRF.

Sensory assessment.

As one of the common complications evaluated by clinicians after DRF is loss of sensation due to median, ulnar, or radial nerve compression neuropathies (Cooney et al., 1980; Steward et al., 1985b), the need for valid, reliable, and responsive clinical sensibility testing becomes paramount to quality of patient care (Bell-Krotoski, Weinstein, & Weinstein, 1993; Strauch et al., 1997). Sensibility testing consists of assessing a wide spectrum of tissue-specific sensory modalities, such as protective skin sensation (Bell-Krotoski et al.), constant touch, pressure, vibration perception (Dellon et al., 1992), and moving one or two-point discrimination (Dellon, 1978). Objective sensibility testing should reliably quantify sensory loss without being affected by patient cognitive influences, such as re-education and

intra- or inter-tester force application variability (Bell-Krotoski et al.).

Most clinical sensibility testing instruments fail to meet objective criteria because they have low sensitivity and reliability (Bell-Krotoski et al., 1993). The two current sensibility tests with high sensitivity and reliability are the Semmes-Weinstein monofilaments (Bell-Krotoski & Tomancik, 1987) and Dellon's pressure-specifying sensory device (Bell-Krotoski, 1991; Dellon et al., 1992). They have easily reproducible instrumentation and allow the tester to apply similar pressures to the examined hand cutaneous region with repeated testing. As both of these tests involve complex instrumentation that requires lengthier exams, clinicians have been using much quicker sensibility screening tests such as the static two-point (Moberg, 1958) or the moving two-point discrimination (Dellon, 1978; Bell-Krotoski et al.) test. Both of these tests lack strong objectivity and reproducibility since the consistent application of the same force by the same or different testers is difficult to control (Strauch et al., 1997). None of the aforementioned sensibility tests psychometric properties have been exclusively determined for DRF patients.

Strauch et al. (1997) described the Ten-Test, intending to mitigate the degree of complexity presented by other previously established sensibility testing

(e.g., Semmes-Weinstein monofilaments), for the purpose of establishing a rapid, reliable, and responsive screening sensibility assessment tool viable for today's fast-paced clinical health-care environment. The Ten-Test is used to assess sensibility via moving light touch applied over a sensory compromised area. Sensibility deficit is graded by the patient on a scale of 1 to 10, with higher scores indicating lesser amount of sensory loss. The value of 10 represents normal sensory status and is assigned to the compared contralateral normal side. After lightly stroking the normal side with a finger tip and indicating to the patient its represented value of 10, the tester lightly strokes both the normal and affected sides simultaneously and with equal pressure before the patient grades the perceived severity of sensory loss at the affected side. The final score is based on a ratio of the value assigned by the patient for the affected side (numerator) and the value of 10 which represents the normal body region (denominator).

The Ten-Test has been validated with the Semmes-Weinstein Monofilaments Test for patients with peripheral nerve disorders, demonstrating a high degree of correlation ($r= -0.71$, $p < 0.05$). Both its intra- (ICC = 0.90) and inter-tester reliabilities (ICC = 0.91) have been determined to be high (Strauch et al., 1997). Patel and Bassini (1999) compared the Ten-Test to the gold-

standard Semmes-Weinstein Monofilaments Test among a large sample of 612 normal subjects and 153 patients with carpal tunnel syndrome. They concluded that the Ten-Test is as reliable and sensitive as the Semmes-Weinstein Monofilaments Test but it offers a more rapid, simple and inexpensive instrumentation. It also measures sensibility on a continuous analog scale, which is more compatible for research related inferential statistics as compared to the ordinal scale of increasing unequal intervals in the Semmes-Weinstein Monofilaments Test.

The Ten-Test current validation among patients with upper extremity nerve compression disorders, including carpal tunnel, strengthens its clinical use among DRF patients. Wrist median nerve compression is among the most common neurological complications post DRF (Cooney et al., 1980; Dennison, 2006). The Ten-Test psychometric properties, including its MCD and MCID values, for patients with DRFs have yet to be determined.

Wrist proprioception assessment.

The sensori-motor control system encompasses both conscious and unconscious senses for optimum joint stability (Riemann, Myers & Lephard, 2002; Riemann & Lephart, 2002a). Assessment of the unconscious wrist sensori-motor control system pathways following DRF has yet to be determined. Testing of the unconscious wrist proprioceptive pathway, which is primarily initiated by

ligamentus afferent receptors (Johansson et al., 1991; Sjolander et al., 2002), would require complex laboratory methods. In contrast, testing of the conscious wrist sensori-motor control system pathway is readily attainable in a busy clinical setting via assessing active wrist JPS (Hagert, 2010). Limited research has been conducted on conscious wrist sensori-motor impairment following DRF.

Standardized testing procedures have been proposed for passive and active wrist JPS testing. Keeping the subject blindfolded during these tests is required (Myers & Lephart, 2000; Riemann, Myers, & Lephard, 2002) since proprioceptive input from visual afferent centers could play a complementary role on sensori-motor joint control (Riemann & Lephart, 2002a). In passive JPS assessment, the tester moves the wrist into the predetermined angle until the subject reports that the joint angle of interest has been reached (Hagert, 2010). The psychometric properties for passive wrist sensori-motor pathway assessment techniques following DRF have yet to be determined.

During active wrist JPS assessment, the subject is asked to reproduce a predetermined joint angle, which is measured with a standard goniometer (Hagert, 2010). In a resent study by Karagiannopoulos et al. (2013), active wrist JPS was assessed via a goniometric technique in

which participants were seated facing a medical plinth. The involved elbow was positioned on the medical plinth in a flexed position with the forearm and wrist in a neutral position and fingers in a resting, flexed position. A standard goniometer with a central 360° scale marked in 1° increments and two 17 cm long arms was used. The goniometer was placed over the volar wrist with its moving arm aligned palmary with the third metacarpal, stationary arm placed at the distal forearm, and axis adjacent to the wrist.

In the Karagiannopoulos et al. (2013) study, active wrist JPS testing followed a standardized protocol. The examiner showed participants a reference wrist position by passively moving the wrist into 20° of extension with the goniometer placed volarly to the wrist. Participants were asked to memorize this angle holding the position for 3 sec. The goniometer was removed from the wrist and the participant was then asked to move the wrist into a fully flexed position prior to moving into wrist extension, reproducing the previously memorized angle. When participants verbally confirmed that the target angle had been attained, the examiner measured the final wrist active ROM. The angular difference between the referenced and actively reproduced wrist angles was used as the JPS deficit criterion value. The greater the angular difference the greater the JPS deficit. A zero

value was assigned when exact reproduction of the referenced wrist extension angle was attained. Positive or negative values were assigned for angular differences greater or lesser to the referenced angle, but only the absolute values of the recorded angular differences were considered for data analysis. The intra-tester reliability of this test were reported to be high (ICC = 0.85). The MDC and MCID values of this test have yet to be determined.

Conservative Management of Distal Radius Fracture

Over the last 20 years, DRFs management has evolved as a result of increased understanding and experience acquired via applying conservative treatment (Krischak et al., 2009). Although surgical management is becoming increasingly more popular for proper DRF healing and earlier return to function (Krischak et al.; Lozano-Calseron, Souer, Mudgal, Ring & Jupiter, 1999), the long-term outcome superiority of surgical management for most DRFs is still uncertain as compared to nonsurgical treatment (Handoll & Madhock, 2003a). Closed reduction with cast immobilization has historically been the primary treatment for the majority of DRFs (Handol et al., 2006; Ilyas & Jupiter, 2007), especially for extra-articular stable as well as minimally displaced and comminuted DRF (Laseter & Carter, 1996).

Closed Reduction Decision

Currently, DRFs are treated conservatively with a 3- to 6-week period immobilization via plaster casting, soft bracing, or a combination of both, depending on the initial fracture severity (Handol & Madhok, 2003b). Closed reduction is performed prior to casting to establish adequate fracture quality and stability if a DRF is intra-articular and significantly displaced. Thus, the decision on performing closed reduction manipulation is heavily based on the DRF severity (Handol et al., 2006). In a study by Kelly, Warwick, Crichlow, and Banister (1997), 30 patients with minimally displaced DRFs, 65 years of age and older, were randomly assigned to a closed reduction or a no reduction manipulation group. Both groups were treated with cast immobilization. No significant differences in radiological findings and fracture displacement existed between the two groups upon cast removal at 5 weeks. A mean of 2 mm radial shortening was recorded in both groups. Similarly, no difference in functional outcomes, objective measures (i.e., pain, wrist AROM, grip strength), cosmetic deformity, or complications were noted at 13 weeks post treatment. They concluded that manipulation of minimally displaced DRFs in this age group is not necessary. Similar research outcomes among DRF patients younger than 65 years of age have yet to be reported.

Types of Conservative Treatment

Comparison of different types of casts or braces on DRF patients who were treated conservatively has been reported in several studies. Kongsholm, Buring, Lindh and Duarte-Martins (1981) conducted a randomized control trial comparing the efficacy of below-elbow plaster cast and dorsal forearm splint held by elastic bandage on 106 DRFs following closed reduction. All cases were extra-articular and multi-fragmentary DRFs, based on the Frykman's classification system (Frykman, 1967). After the end of a 5- to 6-week immobilization period, the incidence of loss of fracture reduction was 10 and 27% for the plaster cast and dorsal splint, respectively. These statistically significant results indicated that below-elbow plaster cast immobilization resulted in a better type of fracture immobilization, leading to better treatment outcomes post DRF.

Two similar studies by Abbaszadegan, Conradi, and Jonsson (1989) and Dias, Wray, Jones, and Gregg (1987) recruited a total of 177 patients with minimally or non-displaced DRFs to compare two different types of immobilization. Patients were randomly assigned to a minimal immobilization via elastic bandage group or a regular cast immobilization treatment group of 4 (Abbaszadegan et al.) and 5 (Dias et al.) weeks,

respectively. Significantly less radial deformity among the bandaged patients was found at 8 weeks by Abbaszdegan et al. No difference in radial deformity between patient groups was found 3 months after treatment by Dias et al. In both trials, physical measures (i.e., pain, ROM, grip strength) and functional recovery were found to be significantly better among DRF patients treated with elastic bandage immobilization by 3 months. Both research groups concluded that treatment of minimally displaced or non-displaced DRFs with elastic bandage immobilization was a better treatment option than cast immobilization, which allowed for earlier mobilization and quicker functional recovery.

Ferris, Thomas, Dewar, and Simpson (1989) conducted a small randomized control trial on 47 DRF patients (27 to 87 years of age) to compare two different types of immobilization. Patients were randomly assigned to a conventional plaster or functional brace treatment group. The brace used in this study consisted of 4 curved plastic pieces held circumferentially by straps around the distal forearm, which was positioned in full supination. The brace allowed 45 and 30º active ROM in extension and flexion, respectively. Radiographic, active wrist ROM, grip strength, and hand edema assessments were conducted at the end of a 5-week immobilization and 9-week post treatment period.

Results of the Ferris et al. (1989) study indicated that patients in the brace group demonstrated less radial dorsal displacement and required re-manipulation less frequently at the end of the immobilization treatment. Similarly, the brace group showed better active ROM and grip results at the end of the immobilization. The brace group had significantly more hand swelling at the end of immobilization but edema levels were fully equalized between groups by 9 weeks. Radiological, active ROM, grip, and edema outcomes were not significantly different between treatment groups at 9-weeks post treatment. They concluded that both the brace and plaster cast are equally efficacious in long-term DRF position stabilization. However, the brace could lead to superior short-term functional outcomes due to earlier active ROM and strength gains as compared to plaster cast treatment. The brace was better tolerated by the patients due to its light weight and freedom of motion. The increased hand swelling observed after brace removal was due to extra circumferential compressive forces applied by the splint around the wrist. Post immobilization treatment would require additional medical supervision for edema control in the brace group.

Cornwall, Ghillani, and Levine (2000) compared the radiological outcome of above and below-elbow plaster casting in 127 adult DRF patients after having a closed

reduction manipulation. Immobilization duration was an average of 6 weeks. Patients were assessed for radiological changes until fracture healing (mean = 41 days). There was no statistically significant difference between the two treatments in volar tilt, radial inclination, or radial length with patient age, gender, initial fracture displacement, and fracture classification being controlled. They concluded that using an above-elbow cast immobilization in the conservative treatment of both stable and unstable DRFs was unnecessary.

A British prospective randomized control trial by Ledingham et al. (1991) studied the efficacy of a plaster-based functional cast, incorporating the same three-point fracture loading pattern at the distal forearm utilized in subsequent studies by Moir et al. (1995) and Tumia et al. (2003). This functional plaster cast was applied with the forearm pronated and extended to the radial styloid process, allowing for wrist flexion and extension active ROMs but restricting forearm rotation. Sixty gender, age, and hand dominance matched DRF patients were randomly assigned to a conventional below-elbow plaster cast (mean age = 60 years) or a functional plaster cast (mean age = 61 years) treatment group immediately post closed reduction. Both groups were

immobilized for 5 to 6 weeks, and their fracture characteristics were comparable at treatment onset.

Ledingham et al. (1991) reported that all patients were assessed upon cast removal and at 12 and 26 weeks post treatment on radiological findings, functional outcomes, and complication incidence. Upon cast removal, the functional cast treated patients showed significantly better fracture stability and functional recovery, which was measured via the Gartland and Werley (1951) scoring system, than the regular cast treated patients. No significant differences on radiological findings existed between the two groups at the 12- and 26-week follow up assessments. However, significantly better functional recovery levels were recorded at 12 weeks in the functional cast group. No significant difference on functional recovery existed between the two groups at 26 weeks post treatment. The incidence of superficial radial nerve compression was significantly higher among patients treated with the functional cast. In contrast, median nerve compression incidence was not significantly different between the treatment groups upon cast removal. Between group radial and median nerve compression incidence was not significantly different at either of the follow-up time periods.

Ledingham et al. (1991) concluded that the functional brace offered superior short-term functional

outcomes since it allowed for early wrist mobilization and better hand function during and after treatment without compromising fracture stability. However, the functional plaster cast was not suitable for application by inexperienced medical personnel. It required experience in both plastering application and understanding of its operational principles. Development of a prefabricated thermoplastic functional splint with the desirable loading properties would resolve application issues related to experience.

Both Moir et al. (1995) and Tumia et al. (2003) conducted a prospective randomized controlled trials to compare the efficacy of a functional prefabricated plastic forearm clam-shell brace (Aberdeen Colles' fracture brace) to the conventional plaster cast. The splint consisted of dorsoradial and volarulnar pieces connected by Velcro straps that formed a three-point compression system around the distal forearm. The splint was applied over a thick layer of stockinette immediately post closed fracture reduction.

Moir et al. (1995) recruited 85 DRF patients who were randomly assigned to a brace or cast group. Despite randomization, the brace group had slightly fewer severely displaced fractures based on the Frykman classification system. Both groups were immobilized for 5 to 6 weeks and assessed upon end of immobilization as

well as at 8, 13, and 26 weeks post injury. Patient outcomes were assessed on pain, grip and pinch strength as well as functional recovery based on the Gartland and Werley (1951) scoring scale. Edema, finger stiffness, and radiographic assessments were conducted at 10 days after reduction and upon cast or brace removal.

Results of the Moir et al. (1995) study indicated that loss of fracture reduction was comparable for both groups at the end of the immobilization period. Functional and pinch strength scores were significantly better for the brace group throughout all assessment time periods. Grip strength was significantly better in the brace group only up to 8 weeks. By 13 weeks, both groups had comparable grip strength scores. Upon treatment termination, patients in the brace group had significantly less pain, swelling, and finger stiffness. Pain levels remained significantly better up to 8 weeks post treatment in the brace group. They concluded that the fracture brace resulted in superior functional outcomes as compared to the conventional plaster cast treatment, despite the fact that more complications (superficial radial nerve and median nerve compressions) were recorded in the brace group.

Tumia et al. (2003) recruited 339 DRF patients who were stratified into two groups. The first group consisted of minimally displaced DRFs that did not

require reduction. The second group consisted of displaced DRFs that required closed reduction. Patients in each group were treated for 5 to 6 weeks immobilization with either a plaster cast or the same forearm brace used in the Moir et al. (2001) study. All patients were assessed for function via the Gartland and Werley (1951) scoring system at 8, 12, and 24 weeks post treatment. A radiological assessment was completed at 10 days and 5 weeks post treatment. Pain and grip strength was assessed at 10 days; and 5, 8, 12, and 24 weeks post treatment.

Results of the Tumia et al. (2003) study showed no statistically significant difference between treatment groups in regards to the fracture reduction levels, pain, and functional scores. Patients with close reduction had significantly higher functional scores than non-manipulated patients. Significantly better grip strength was seen in the brace group only during the early stages of treatment (10 days to 5 weeks). This study’s results supported the use of a brace as a conservative treatment of DRFs whether or not closed reduction manipulation was performed. They concluded that the brace treatment offered comparable pain, functional, and anatomical results as compared to the plaster cast immobilization treatment. An important advantage of the brace treatment was its ability to allow for early wrist motion,

especially during early treatment, resulting in significantly better grip strength values.

In a prospective randomized multi-centered trial, Grafstein et al. (2002) compared the efficacy of a below-elbow plaster cast, a volar-dorsal forearm brace, and a modified sugar-tong fiberglass splint in the treatment of 101 extra-articular, multi-fragmentary DRFs following closed reduction. All patients were 18 years of age and older and were assessed at 4 weeks post immobilization for radiological fracture characteristics and loss of reduction. Functional assessment was performed at 2 and 6 months using the DASH and SF-36 scales. All patients had similar fracture characteristics before reduction. No significant difference was found among the treatment types on preventing loss of reduction at 4 weeks post immobilization. No significant difference in long-term functional status was observed among treatment groups. They concluded that either plaster cast or volar-dorsal splints was equally efficacious in the conservative treatment of DRFs while both offered adequate patient comfort based on their ease of application.

Duration of Conservative Treatment

Although not a single treatment-duration option exists that is proven to be the gold standard, the duration of DRF immobilization treatment depends on the

potential of fracture re-displacement to an undesirable level (Christensen, Christiansen, Krasheninnikoff, & Hansen, 1995). Most DRFs are known to shift from their original position within the first 2 weeks of immobilization (Solgaard, 1986). Although all DRFs reach union with some degree of malposition during immobilization (Dias et al., 1987), loss of DRF position is less likely to occur (less than 10%) after the initial first 2 weeks of immobilization (Abbaszadegan et al., 1989). The short- or long-term efficacy of various lengths of immobilization treatments on DRF has been studied.

The short-term benefits of early mobilization was determined by Davis and Buchanan (1987) who randomly assigned 56 minimally displaced DRFs to a 2- or 5-week immobilization treatment group. Patients in the early mobilization group had their plaster cast removed at 2 weeks and replaced by a double-layer elastic tubigrip support. Both patient groups had comparable age averages (55.6 and 56.6 years), gender ratios, and fracture characteristics. All patients were assessed for function using the Gartland and Werley’s (1951) scoring method at 5 and 7 weeks post treatment. Grip strength was assessed at 2, 5, and 7 weeks post treatment. Pain was assessed at 1, 4, and 6 weeks post treatment. A radiologic assessment was completed at 5 weeks and patient satisfaction was

assessed at 7 weeks post treatment. Results of this study showed no significant difference in pain between groups. The early mobilization group demonstrated significantly better function at 5 and 7 weeks post treatment. Grip strength was not significantly different between groups. Radiologic findings at 7 weeks were comparable for both groups. Early mobilization was the treatment of preference in terms of patient satisfaction. They concluded that the most efficacious and cost-effective treatment method for minimally displaced DRFs was a short duration of immobilization followed by tubigrip support that allowed for early mobilization and return to function.

McAuliffe et al. (1987), Christensen et al. (1995), and Vang Hansen, Straunstrup, and Mikkelsen (1998) studied the long-term efficacy of early mobilization up to 1-year post DRF treatment. All three studies compared a 3-week to 5-week immobilization treatment via below-elbow plaster casting post DRFs. The McAuliffe et al. study enrolled 108 DRF female patients, 60 years of age and older, who were randomly assigned to a 3- or 5-week immobilization treatment after closed reduction. Patients were assessed immediately after and at 3 and 12 months post treatment. Outcome measures were fracture characteristics via the Sarmiento criteria (Sarmiento, Pratt, Berry & Sinclair, 1975), function via the Gartland

and Werley (1951) scoring system, pain, wrist active ROM, and grip strength. No significant differences between groups in fracture characteristics, wrist active ROM, or functional scores were found at the three assessment time periods. At 3 months following treatment, the 3-week treatment group had significantly better pain response than the 5-week treatment group. No between group significant difference in pain levels was observed at 12-months post treatment. At 12 months, the 3-week treatment group showed significantly better grip strength than the 5-week group. They concluded that the shorter immobilization treatment allowed for early mobilization and did not compromise fracture stability. Instead, it led to less pain in early stages as well as greater grip strength in later stages after treatment.

Christiancen et al. (1995) recruited a small sample of 33 DRF patients (mean age = 64 years) and incorporated study methodology similar to the McAuliffe et al. (1987) study to assess patients at 3 and 9 months after immobilization treatment. All DRF were classified as minimally displaced fractures using the Older et al. (1965) criteria, and they were not reduced prior to immobilization treatment. They found no statistically significant differences between groups in pain and function self-reports impairments (i.e., active wrist ROM and grip strength), radiographic deformity, and

complications at both assessment times. They concluded that both 3- and 5-week immobilization periods were equally effective for the treatment of minimally displaced DRF.

Vang Hansen et al. (1998) incorporated an identical study design to the Christiancen et al. (1995) study to determine the long-term effect of immobilization in a larger sample (n = 100) of DRF patients at 1 year following treatment. DRFs were classified as minimally displaced based on the Older et al. (1965) criteria. Assessments of fracture characteristics, pain, wrist active ROM, and grip strength were completed upon cast removal and 1-year after treatment. They reported no significant difference between groups in all of the aforementioned measures at both assessment times. They concluded that a 3-week immobilization treatment was the preferred treatment for minimally displaced DRFs.

Millett and Rushton (1995) investigated the long-term effects of cast immobilization at 3-years post DRF treatment. Ninety DRF female patients were randomly assigned to a 5- or 3-week immobilization treatment that consisted of a below-elbow plaster cast. DRFs were classified via the Frykman Classification System (Frykman, 1967). DRFs with both minimal and extensive levels of displacement and comminuttion were included in the study. Patients in the 3-week cast immobilization

group received an additional 2 weeks of a flexible cast immobilization. Displaced fractures were treated with closed reduction in both groups. Both groups had comparable patient demographic and radiographic values. Assessments of radiographic findings and pain were assessed at 1, 3, and 5 weeks; 3 and 6 months; and 3 years post treatment. Wrist active ROM and grip strength were assessed at the same time intervals, starting at 5 weeks following treatment.

Millet and Rushton (1995) reported no significant difference in fracture stability loss and pain between groups throughout all times. Earlier mobilization patients showed greater satisfaction and significantly greater AROM and grip strength at 3 and 6 months post treatment. At 3 years, no significant difference existed between the two groups in wrist active ROM and grip strength. They concluded that early mobilization promoted both earlier functional recovery and patient satisfaction, which was not detrimental to long-term recovery.

Treatment Forearm Position

Sarmiento et al. (1975) proposed a method of treatment for comminuted intra-articular DRFs with an above-elbow cast, which placed the elbow in flexion, the forearm in supination, and the wrist in flexion and ulnar deviation. This cast was replaced several days later with

a below-elbow brace, which allowed elbow motion and wrist flexion but prohibited wrist extension as well as forearm pronation and supination. The proposed mechanism for the supinated forearm position was based on preventing the deforming action of the brachioradialis muscle on the distal radius fragment, reducing radial fragment dislocation dorsally and volary via ligamentotaxis, and preventing radius shortening via tightening of the radial collateral ligament. Concurrently, a supinated forearm allowed full exercise of the hand and wrist in flexion for functional AROM. Radiographic outcome findings indicated that this treatment approach resulted in only minimum distal radius fragment displacement while finger stiffness and hand edema were significantly controlled via early use of active ROM.

The efficacy of this type of treatment was tested in a large prospective randomized control trial by Stewart et al. (1984). This study recruited 243 patients with various degrees of displaced extra- and intra-articular Colles' fractures. All patients were randomly assigned to one of three 6-week immobilization treatments: a regular below-elbow plaster cast with forearm in pronation, above-elbow brace with forearm in supination (Sarmiento brace), or below-elbow brace with forearm in neutral. All of the treatment groups were comparable for gender, age, hand dominance, and fracture severity. Patients were

assessed on radiographic findings, based on loss of reduction, at 6 weeks, as well as 3 and 6 months post treatment. Functional assessment via clinical interview using the Gartland and Werley (1951) criteria was performed at 3 and 6 months. There were no significant differences among the three treatment types in loss of fracture reduction and patient's function at all assessment time-periods. They concluded that use of the below-elbow plaster cast immobilization was the better treatment choice since the use of a long-arm brace with the forearm in supination did not add any clinically significant anatomical and functional benefits.

Handol and Hadhock (2003b) conducted the latest reported systematic review on conservative DRFs interventions. In this review, 35 studies met inclusion criteria for their analysis. Their results indicated that research on various conservative DRFs interventions present conflicting evidence that is negatively affected by lack of available trials and methodological flaws. There is insufficient evidence from current randomized controlled trials to determine which conservative treatment methods are the most efficacious for DRFs among adults. Controversial issues relating to conservative DRF treatment include the decision to perform closed reduction manipulation prior to casting, the type of immobilizing method (i.e., plaster cast versus a splint),

the duration of immobilization, and the position of the forearm during immobilization. They concluded that DRF should be treated conservatively via accepted techniques with which physicians have high degree of familiarity. Physicians' treatment decision should also be enhanced by considering other factors such as treatment cost-effectiveness, patient's preferences and functional demands, and circumstances leading to high risk of treatment complications.

Although some of the aforementioned trials provided good evidence for certain types of DRF conservative treatment, several can be criticized for their lack of result comparability (e.g., variability in sample size, injury severity, treatment execution, length of follow up) and critical methodological flaws. The vast majority of the aforementioned studies can be criticized for methodological flaws that include inadequate sample size, lack of assessor blinding, lack of proper allocation concealment, and use of non-validated functional scales (i.e., Gartland and Werley scale) with no proven association to functional outcomes. Other limitations include inadequate description of inclusion criteria, incomplete description of trial interventions, and reporting of high patient attrition at follow up (Handoll and Madhok, 2003b).

There is no strong conclusive evidence for the use of closed reduction post DRF. Although most of studies provided good evidence for the efficacy of a regular below-elbow plaster cast immobilization treatment for DRFs, more attention needs to be directed on the benefits offered by the functional splints, which seem to provide both good fracture stability and early functional recovery. Some promising evidence exists for the use of minimum support or elastic compression bandaging for the treatment of minimally displaced DRFs as it produced significantly better radiological and functional outcomes when compared to traditional plaster-cast immobilization.

Furthermore, the use of shorter cast immobilization times for 3 to 4-week periods seem to offer better functional results without a compromise of the fracture stability, especially for minimally displaced DRFs. There is no strong evidence to support different types of cast material or forearm immobilization in a supinated position. Likewise, there is no conclusive evidence to support use of no immobilization as compared to traditional immobilization treatment. The overall available evidence from randomized controlled trials has been inadequate to establish a strong consensus for the superiority on all proposed conservative treatment techniques (Handoll and Madhok, 2003b). Additional high

quality prospective randomized controlled trials are needed to advance DRF conservative treatment.

Surgical Management of Distal Radius Fracture

Decision making as to whether proper management of a DRF is warranted via an operative approach is not always clear. In many instances, physicians confront a certain degree of uncertainty as to which approach would be most appropriate for the most effective outcome. Not a single surgical option exists that is proven to be the gold standard for all DRFs (Raia & Catalano, 2007). When making surgical treatment decisions, physicians consider radiographic findings on bone integrity, fracture displacement and stability (Ilyas & Jupiter, 2007; Simic & Weiland, 2003), as well as patient factors (e.g., lifestyle, age, functional level, mental status, compliance with treatment), all of which can influence the final treatment outcome (Ilyas & Jupiter).

Surgical intervention becomes the main treatment option when an acceptable reduction cannot be achieved or maintained by conservative means of closed reduction combined with a cast or brace immobilization (Simic & Weiland, 2003). When the treatment decision is not clear, physicians often elect to monitor fracture position during an initial conservative treatment (i.e., closed reduction and cast immobilization). If fracture

instability is present, fracture position loss insidiously occurs within 10 to 14 days, a period which is associated with inherent risk of developing fracture malunion (Lasseter & Carter, 1996).

As the degree of fracture instability is one of the main criteria for determining the proper type of DRF treatment (Lasseter & Carter, 1996), surgical management becomes justified for those DRFs classified as unstable (Stewart, Innes & Burke, 1985a). It is widely accepted among physicians that significantly comminuted and intra-articular DRFs are intrinsically unstable and lead to the poorest functional results (Lasseter & Carter, 1996). In addition to achieving stable fixation with proper anatomical alignment, surgical approaches allow for early motion, helping to avoid the deleterious effects of prolonged immobilization on articular and soft tissue structures (Simic & Weiland, 2003). Thus, early recognition and detection of unstable DRFs that present poor potential to respond to conservative management is needed to maximize treatment efficacy.

Several earlier studies identified predictive factors for DRF instability warranting surgery. Stewart et al. (1985a) determined that significant dorsal comminution, radial shortening, dorsal tilt, and intra-articular displacement of the distal radius predicted loss of fracture position in the cast. Lafontaine, Hardy,

and Delince (1989) showed that dorsal radial angulation of greater than 20º, dorsal comminution, radio-carpal intra-articular fracture line, concomitant ulnar fracture, and greater than 60 years of age were risk factors for DRF instability. Lafontaine et al. concluded that the presence of three or more of these factors leads to failure of conservative management.

More recent studies have also delineated clear criteria for surgical DRF management. MacKenney, McQueen, and Elton (2006) proposed that age and dorsal comminution are the most important predictive factors for both early and late DRF instabilities. Simic and Weiland (2003) concluded that DRFs with loss of ≥ 2 mm of radial height, loss of radial inclination of ≥ 5°, loss of volar tilt of ≥ 10°, and loss of the distal radioulnar joint congruency with presence of > 1 to 2 mm of intra-articular step-off should be surgically reduced. According to Ilyas and Jupiter (2007), significant degree of DRF instability can be predicted by dorsal comminution greater than 50% of the distal radius width, intra-articular disruption, palmar comminution of the distal radius, dorsal tilt greater than 20º, fragment translation greater than 1 cm, radial shortening greater than 5 mm, concomitant ulnar fractures, and severe osteoporosis. Timely recognition of these factors would prevent unnecessary conservative

treatment and enhance a decision on proper surgical management.

There are other conditions associated with DRFs that may warrant surgical management. These involve multi-injury patterns that include compound DRFs, bilateral DRFs, and concomitant fractures of the upper extremity (e.g., ulnar or various types of carpal fractures). In addition, acute median nerve compression due to increased volar forearm compartment pressure post injury may necessitate an urgent surgical repair of the DRFs combined with carpal tunnel release. (Ilyas & Jupiter, 2007)

Operative Treatment Techniques

DRF surgical management decisions may be based on a wide spectrum of operative methods that encompass both limited open and more invasive fracture reduction with plating techniques. Closed reduction combined with percutaneous pinning and cast immobilization was first popularized in the mid 1960s as the most effective method for anatomic DRF reduction (Green, 1965). This invasive technique has evolved through the years despite its disadvantages that include unsatisfactory results relating to long immobilization effects, loosening of the pins, pin site infection, inadequate restoration of

palmar tilt, and lack of pin adjustability (Carrozzella & Stern, 1988; Cooney, Linscheid & Dobyns, 1979).

Currently, percutaneous pinning is considered to be a minimally invasive method reserved only for extra-articular DRFs that are projected to get re-displaced if treated only conservatively. The pin and plaster technique can be effective when the distal radius is not severely comminuted or osteoporotic. Various pinning methods have been proposed that include two or more pins placed transradialy or transulnarly at various angles to reach and stabilize distal radial fragments. Despite advancing knowledge, the pins and plaster are often a difficult to apply technique since molding a cast around transcutaneous pins could lead to re-displacement of the distal radial fragment (Simic & Weiland, 2003). The pins and plaster treatment has been associated with a significant loss of fracture reduction in 25 to 33% of patient cases (Taras, Kimberley, Zambito, & Abzug, 2006) and it has lost its current popularity (Simic & Weiland, 2003).

When both the distal radius and radiocarpal joint are severely comminuted and their stability is significantly compromised, stronger operative management is warranted via external or internal fixation (Simic & Weiland, 2003). The use of external fixation devices becomes a viable treatment option when conservative

treatment is considered incompetent to maintain fracture reduction for certain unstable DRFs (Handoll, Huntley, & Madhok, 2007). External fixation devices use an external metal frame that is attached to percutaneous pins or screws inserted into the distal hand at the metacarpals and radius (Handoll et al.; Simic & Weiland). Applying an external fixation device entails a minimally invasive procedure in which the fractured site is not exposed and small incisions in the skin are used for pin insertion only. Fracture reduction is typically completed via closed means prior or during pin insertion (Handoll et al.).

There is a wide variety of external fixator devices, which typically are classified as bridging and non-bridging (Simic & Weiland, 2003). Bridging external fixators inter-connect the metacarpals and the radius as they cross the radial fragment. Non-bridging external fixators insert their distal pin at the radial fragment for direct fracture stabilization (Handoll et al., 2007). Typically, a bridging external fixation device applies distraction to the distal radius and places the hand in a flexed and ulnarly deviated position (Simic & Weiland). Thus, DRF treatment via a bridging external fixation device attempts to restore distal radius stability and proper alignment via the principle of ligamentotaxis (Lasseter & Carter, 1996; Raia & Catalano, 2007) in which

fracture realignment is achieved via traction of the surrounding capsuloligamentous structures (Lasseter & Carter). The treatment duration with an external fixator is typically between 5 to 8 weeks and is followed by wrist active mobilization (Simic & Weiland).

DRF treatment with an external fixation device has been considered an effective treatment method for restoring and maintaining proper radial length and volar tilt among DRF patients with severely comminuted fractures that are affected by osteoporosis (Fu et al., 2006). It also offers a stable external base for stabilization of severely comminuted intra-articular DRFs. A stable external fixator offers a greater stabilizing surface, allowing for proper reconstruction of the radiocarpal joint congruency. It also protects the healing fracture from destabilizing forces that originate from contracting forearm muscles (Simic & Weiland, 2003).

External fixators have improved DRF stabilization when compared to percutaneous pinning alone but with the expense of much higher complication rates (Dunning et al., 1999). Common complications include increased pin track infections, iatrogenic metacarpal fractures, and dorsal sensory branch irritation of the radial nerve (Dunning et al.; Handoll et al., 2007). Although external fixation devices are known to maintain proper radial length, full healing of underlying radius fracture

fragments may still not occur (Dunning et al.) and proper distal fragment volar tilt may not be restored (Laseter & Carter, 1996). External fixation treatment augmentation with percutaneous pinning can often provide sufficient fracture stability (Braun & Gellman, 1994; Dunning et al.; Handoll et al.; Seitz, Froimson, Leb, & Shapiro, 1991), especially for adequate restoration of dorsally displaced distal radius fragments. When distal radius fragment pinning is needed, it is applied after the frame of the external fixator has been applied (Simic & Weiland, 2003).

When pinning with cast immobilization and external fixation devices do not offer reasonable treatment options for DRFs reduction stability, open reduction with internal fixation (ORIF) via plating should be considered (Raia & Catalano, 2007). ORIF is typically reserved for complex intra-articular DRFs that are significantly fragmented, impacted, displaced, and not reducible via longitudinal traction, pinning or other conservative treatment methods (Bradway et al., 1989; Knirk & Jupiter, 1986; Melone, 1986). Both dorsal and volar platting treatments have been used for DRF surgical stabilization via ORIF. They are traditional plate and screws compression mechanisms that stabilize the DRF site via using the frictional force between the bone and the plate to counteract external forces imposed at the fracture

site. Fracture proper alignment and stability is achieved via screw torque, which leads to fracture site edge compression (Strauss, Schwarzkopf, Kummer, & Egol, 2008).

The original type of dorsal plates (also known as osteosynthesis pi-plates) was associated with high complication rates of extensor tendon irritation and rupture (Kambouroglou & Axelrod, 1998). With advancing knowledge and technology, the original dorsal plates have been redesigned to lower profile systems. These new dorsal plates are thinner and the screws sit flush with the plate (e.g., Lo-Con T Plate), lowering the potential for extensor tendon attrition (Kamath, Zurakowski, & Day, 2006; Simic et al., 2006).

Regardless of the plate profile properties, dorsal plating surgery disrupts the dorsal extensor mechanism at the wrist and violates vital periosteal blood supply to smaller cortical fracture fragments at the dorsal radius (Henry, Griggs, Levaro, Clifton & Masson, 2001). Dorsal plating technique requires full dissection of the third extensor compartment as well as separation of the second and fourth dorsal compartments from the cortical floor for plate insertion (Henry et al.; Ring & Jupiter, 1999). Plate insertion disrupts the natural formed fibro-osseous tunnels of the extensor compartments on the dorsal surface of the distal radius (Henry et al.). Although

using a flap of the extensor retinaculum to cover the plate and create a protective layer inferior to the extensor tendons are recommended (Kamath et al., 2006), this method does not recreate normal extensor mechanism anatomy. Separating the extensor mechanism from its distal radius base also leads to the disruption of the vital periosteal blood supply, which may complicate union of smaller dorsal radius cortical fragments that are difficult to repair independently (Henry et al.).

With recent advance in surgical techniques and technologies, volar-plate with a fixed-angle system has been introduced with the intent to eliminate extensor tendon attrition and better address DRF stability, joint congruency, and early return to function (Raia & Catalano, 2007). The rationale for using volar plates is based on the biomechanical nature of DRFs. The majority of both low- and high-energy DRFs displace dorsaly, resulting in osseous failure dorsally due to radial compression and volary due to radial tension. The osteological nature of this fracture pattern typically leads to larger volar and smaller dorsal cortical fragments. Volar platting allows the surgeon to repair DRFs using a more stable surgical approach that primarily addresses the larger volar fragments rather than fixing the smaller dorsal fragments that are more unstable and difficult to fix independently. The fixed angle of volar

plates also allow for precise anatomical restoration of normal radial palmar tilt (Henry et al., 2001).

The volar platting approach offers two additional advantages to DRF surgical repair. First, the pronator quadratus muscle, which is initially detached for surgical exposure of the distal volar radius (Ring & Jupiter, 1999), is typically repositioned over the plate (Henry et al., 2001). This well vascularized muscle flap offers an excellent gliding surface for the flexor tendons and plays a protective role as it covers the plate and volar cortical fragments (Chung et al., 2006; Henry et al.). Thus, a repair with minimum flexor tendons attrition potential is achieved. Second, the volar plating technique provides the surgeon with an easier access to the carpal tunnel region, allowing for median nerve decompression via the same incision (Henry et al.).

ORIF with either dorsal or volar platting requires significant surgical exposure and rigid fracture fixation via high plate to bone compression forces. The surgical requirements for ORIF include significant soft tissue stripping that can alter the fracture site histological composition, leading to significant iatrogenic devascularization. Along with the excessive plate to bone compressive forces, ORIF often results in delayed fracture healing, nonunion, and infections. (Strauss et al., 2008)

Recent technological advancements have led to the introduction of a more biologically intact surgical approach that utilizes a locked volar plate design (Strauss et al., 2008). This new method offers an improved fracture stabilization treatment with a fixed angle plate, which does not allow for any angular motion to occur at the plate-screw intersect point (Egol, Kubiak, Fulkerson, Kummer, & Koval, 2004). The central concept of this newly developed technique with locked plating systems is fracture stabilization via bridging plate osteosynthesis. This technique replaced the older concept of fracture stabilization via conventional screw torque and plate-bone interface friction (Strauss et al.).

This new method resembles the concept of an internally placed external fixator but involves less periosteal stripping, leading to less cortical bone compression at the fracture site (Egol et al., 2004). Typically, an external fixator bridges the fracture site with a flexible fixation that induces bone healing via callus formation rather than fracture compression (Gardner, Helfet, & Lorich, 2004). The new locked plating system replicates this biomechanical healing concept via screws locked into the plate, inducing a rigid fixation mediated from plate against bone contact forces in a fixed and stable angle (Egol et al.).

The new plate design with screws being fixed, or locked, into the plate results in a very stable screw-plate construct at a fixed-angle (Egol et al., 2004). Shearing forces between bone and plate are converted to softer contact forces at the plate-bone interface. The angular stability of the locked screws leads to plate-bone contact forces that are dispersed more evenly across all screw-bone interfaces, avoiding areas of excessive compressive force concentration (Gardner et al., 2004). Thus, stronger internal fracture fixation is achieved with less devascularization and bone necrosis risk at the surgical site (Fernandez Dell'Oca et al., 2001). Most new fixed-angle locking plates are currently available with threaded locking screws or smooth locking pegs. The latest biomechanical research has proven that the threaded locking screws provide significantly better stiffness and support against axial compression and torsional forces at the distal radius fragments (Weninger et al., 2010).

Currently, the majority of orthopedic surgeons prefer the use of volar fixed-angle locked plating in DRF surgical management, which is supported by laboratory research (Gardner et al., 2004; Liporace et al., 2005; Weninger et al., 2010). The indications for locked plate fixation include complex peri- or intra-articular, comminuted, and dorsally displaced DRFs, especially for

older DRF patients with poor bone quality (Gardner et al.). Liporace et al. conducted a biomechanical cadaveric study to compare the internal stability offered by non-locked dorsal plates and volar locked fixed-angle plates among unstable and dorsally displaced DRFs. The experiment was conducted on 6 matched pair specimens, which were axially loaded in multiple directions (volar, dorsal, and central). They concluded that the volar locked fixed-angle plate was significantly stronger in all but the dorsal directed direction, maintaining more of its initial strength after repetitive loading.

In a similar biomechanical cadaver study by Trease, McIff, and Tody (2005), volar and dorsal non-locked and locked fixed-angle plates were compared for intrinsic stiffness and failure strength on dorsally comminuted DRFs. In this study, no significant differences existed between volar non-locked and locked fixed-angle plates. However, this study confirmed that the volar locked fixed-angle plates offered a significant advantage on reducing devascularizing cortical bone pressures and tissue disruption at the fracture site.

In the same study, dorsal non-locked and locked plates were found to have significantly greater stiffness and required significantly greater force to reach failure than volar non-locked and locked fixed-angle plates. This was mainly attributed to the biomechanical advantage

of a dorsal plate construct, which acted as a buttress in a dorsally displaced distal radius fragment (Trease et al., 2005). Previous research has shown that as the force distribution on the distal radius changes at different wrist positions (Short, Werner, Fortino, & Mann, 1997), axial loading on a more extended wrist leads to greater loading at the dorsal distal radius (Viegas & Paterson, 1997). Thus, the biomechanical advantage of the dorsal plating construct offers a stronger fracture support against dorsal oriented loading to the distal radius (Trease et al.).

Other biomechanical advantages of the volar plating have also been demonstrated. Osada, Viegas, Shah, Morris, and Patterson (2003) conducted a biomechanical study to compare the strength of 4 dorsal and 2 volar plates commonly used in DRF surgical treatments. This study's experiments simulated extra-articular DRFs in cadavers. All plate types reached their failing points without developing angular deformity greater than 5º. The volar plates offered a statistically significantly higher deformation resistance (up to 250 N forces) prior to their failure. An explanatory factor to fixed-angle volar plating stiffness is its 12º inclination. This design allows an oblique screw orientation that offers stronger resistance to dorsal displacement as well as restores crucial volar cortical continuity (Ruch &

Papadonikolakis, 2006). In addition, the other significant benefits of the volar locked fixed-angle plate include less surgical trauma, ease of plate placement, and fewer surgical complications. These advantages seem to significantly overweigh its proposed biomechanical disadvantage when DRFs are dorsally displaced (Trease et al., 2005).

Volar Plating Clinical Outcomes

Rozental and Blazar (2006) conducted a retrospective study on 41 dorsally displaced, comminuted and unstable DRFs cases treated with a volar fixed-angle plate. Their primary goal was to measure functional outcomes 12 months post surgical repair. Function was assessed using the DASH and Gartland and Werley (1951) scoring scale. All subjects were found to achieve good or excellent functional outcomes with relatively few complications. Complications included 4 cases of loss of reduction and 3 cases of flexor tendon irritation that required plate removal.

Arora, Lutz, Hennerbichler, Krappinger, Espen, and Gabl (2007) used a similar study design to study retrospectively 114 dorsally displaced, comminuted and unstable DRFs cases treated with a volar fixed-angle plate. All patients were assessed for function via the DASH scale, grip strength, wrist active ROM, pain, and

radiographic findings at 12 months post surgery. Final outcomes were classified as excellent in 31 cases, good in 54 cases, fair in 23 cases, and poor in 6 cases. Their surprisingly high complication rate of 27% included most frequently flexor and extensor tendon irritation (57% of all complications). They also recorded 4 cases of flexor and extensor tendon ruptures. Fracture union occurred in all cases. They concluded that in spite of the considerable satisfactory outcomes, surgeons need to be mindful of these possible complications.

Chung et al. (2006) conducted a study to determine if the volar fixed-angle locking plating system is the most efficacious treatment for inadequately reduced, dorsally displaced, and unstable DRFs. In this study, 87 DRFs (mean patient age 48.9 years) who underwent ORIF were recruited and prospectively evaluated at 3, 6, and 12 months after surgery. Outcome measures included radiographic findings, grip and pinch strength, wrist active ROM, and functional status measured via the Jebsen-Taylor Hand Function Test and the MHQ test. All objective and functional measures showed continued improvement up to 6 months, with minimum change between 6 months and 12 months post surgery.

Results of the Chung et al. (2006) showed no clinically meaningful changes for all radiographic parameters at all assessment times. Adjusted for hand

dominance, grip and pinch strength was rated 56 and 81% of normal at 3 months, 72 and 91% at 6 months, and 79 and 97% at 12 months. At 3 months, all wrist active ROM were above 83% except flexion which was 75% of the contralateral side. At 6 months, all wrist active ROM were above 90% except flexion and ulnar deviation, which had improved to 81 and 87% of the contralateral side, respectively. At 12 months, most wrist active ROM values ranged above 95% with flexion and ulnar deviation being at 86 and 82%, respectively. Functional outcome of the Jebsen-Taylor Hand Function Test was 94% at 3 months and reached almost normal values of 98% at 6 months with no further improvement thereafter. MHQ test values improved to 78% at 3 months, reached a plateau value of 83% at 6 months, showing not further significant improvement at 12 months. No tendon or plate complications and only one case of median nerve irritation were recorded. They concluded that a volar fixed-angle locking plating system is effective for treating unstable DRFs with excellent long-term functional results and minimal complication risks.

Figl et al. (2010) conducted a study to determine if loss of fracture reduction could be prevented via using a volar fixed-angle locking plate. They recruited 58 elderly patients (75 years or older) who were surgically treated for osteoporotic, dorsally displaced, and

unstable DRFs. All patients were assessed, on average, at 13 months post surgery for radiographic fracture parameters, wrist active ROM, grip strength, pain, and functional outcomes via the DASH scale. All patients used a custom thermoplastic wrist splint and had physical therapy with early mobilization for 4 weeks immediately after surgery.

Figl et al. (2010) reported that at the final assessment full fracture union occurred in all patients with no radial shortening in 91% of cases. Final radiographic outcomes were classified as excellent in 25 cases, good in 30 cases, and adequate in 3 cases. Active ROM was reduced by 19% in flexion and extension, 13% in radial and ulnar deviations, and 9% in supination and pronation. Adjusted grip strength for hand dominance was 55% higher than the contralateral side. Only minimal mean pain score associated with weight-bearing arm function of 3.4 (visual analogue scale) in 52% of cases was present. The mean DASH score was 28%. Complications were very minimal with one case of flexor tendon rupture and 3 cases of median nerve compression. The authors concluded that volar fixed-angle locking plating offered excellent fracture support in osteoporotic unstable DRFs and lead to outstanding functional results and patient satisfaction.

Results of the four aforementioned clinical outcome studies provide evidence to support the effectiveness of the volar fixed-angle locking plating treatment, which recently has become a common surgical technique for DRFs among orthopedic surgeons. The strongest evidence towards functional outcomes was offered by the results of the Chung et al. (2006) prospective cohort study. Results of the other studies offered weaker evidence due to their retrospective analysis. Recent prospective randomized controlled trials have provided the strongest evidence for the clinical effectiveness of the volar fixed-angle locking plating treatment on DRFs.

Trials Comparing Treatments

Kapoor, Agarwal, and Dhaon (2000) conducted a prospective randomized controlled trial to compare the effectiveness of plaster cast immobilization, ORIF, and external fixation treatments on intra-articular unstable DRFs. In this study, 90 male DRF patients (mean age 39 years) were randomly assigned to one of the three treatments. The duration of cast immobilization and external fixation treatments was 6 to 7 weeks. ORIF treatment utilized Kirschner wires, dorsal non-locking plating, or both. ORIF patients progressed to an early mobilization physical therapy program at 2 weeks post surgery. All patients had displaced intra-articular DRFs

and were followed for 4 years. Patients were assessed for radiographic parameters, grip strength, and function.

Kapoor et al. (2000) concluded that ORIF or external fixation offered the best method for maintaining intra-articular fracture reduction with less risk for secondary joint arthrosis. Plaster immobilization was not sufficient to maintain the reduced fracture, resulting in high incidence of required remanipulation. External fixator was effective for maintaining radial length in severely comminuted DRFs. This study had methodological flows that made its results difficult to generalize. Patient randomization was poorly described, description of inclusion and exclusion criteria was not clearly reported, and insufficient data were provided regarding objective outcome measurements. Functional outcome was measured via a non-validated method, which was based on residual bony deformity and complication rates alone. The available evidence from this trial was inadequate to determine any treatment superiority.

Handoll and Madhok (2003a) conducted the first systematic review with a primary aim to determine the most effective surgical treatment for DRFs in adults. Inclusion criteria were met by 48 clinical trials that compared various surgical interventions for DRFs and published between 1988 and 2002, involving 3,371 adult DRF patients (range 34 to 75 years of age). Compared

surgical interventions consisted of percutaneous pining, external fixation, ORIF with plating, and bony graft filling. Conservative treatment with plaster cast immobilization was also compared to the surgical methods.

In Handoll and Madhok's (2003a) review, 13 trials were used to compare plaster cast immobilization with external fixation in 908 patients, which included various types of displaced extra- and intra-articular fractures. There was sufficient evidence to support that external fixation treatment maintained fracture position and prevented loss of reduction or late fracture malunion better than cast immobilization. However, external fixators were associated with higher incidence of complications such as pin site infections and radial nerve injury. There was insufficient data for subgroup analysis for treatment effectiveness on different types of fracture or patient characteristics.

In the same review, 5 trials were used to compare various percutaneous pinning techniques to plaster cast immobilization. There was some evidence to support the superiority of percutaneous pinning compared to plaster cast immobilization, regardless of type or method. Treatment with percutaneous pinning was superior for maintaining the reduction of an unstable DRF and produced better functional outcomes. Complications with pinning were minor and not significantly higher than cast

immobilization. There were insufficient data for subgroup analysis for treatment efficacy on different types of pinning.

In the Handoll and Madhok (2003a) review, 3 trials compared percutaneous pinning and external fixation treatments and 2 trials compared a combined treatment of pinning plaster immobilization and external fixation to only external fixation. Other secondary treatment comparisons were based on bone grafting methods, arthroscopic techniques, types of pinning methods, and duration of immobilization after surgery. A comparison between different types of ORIF (e.g., volar versus dorsal plating) was not reported due to lack of clinical trials.

According to Handoll and Madhok (2003a) significant heterogeneity existed among population characteristics, fracture severity, type of pinning methods, type of external fixators, and treatment durations in all trials. Also, the use of quasi-randomised methods, data incompleteness, large subject loss to follow-up, small sample sizes, and use of non-validated functional scales threatened the internal validity of several trials. Overall, they concluded that there was insufficient robust evidence to determine superiority amongst the aforementioned compared treatment methods.

The final conclusions of Handoll and Madhok (2003a) systematic review was that the available randomized trials offered insufficient evidence for most of the surgical treatment options utilized by orthopedic surgeons to manage DRFs. Nonetheless, there was some evidence to support the superiority of pinning and external fixators in supporting fracture stability and preventing deformity or loss of reduction better than cast immobilization only. Indications for use of different types of pinning or external fixation and timing or duration of immobilization were not supported by available evidence. Sufficient evidence was not presented to determine the supplementation of external fixation and pinning methods. In addition, there was insufficient evidence to substantiate the projected superior role of ORIF (dorsal plating) and its various methods. Thus, DRF surgical treatment selection is primarily based on criteria that emphasize physician training and experience, as well as complication potential, and patient factors. The optimum DRF surgical treatment is yet to be determined.

In a subsequent systematic review, Handoll et al. (2007) evaluated the evidence from randomized controlled trials on the effectiveness of external fixation devices and conservative treatment for DRFs. Inclusion criteria were met by 15 trials published between 1988 and 2006,

involving 1,022 adult DRF patients (range 36 to 72 years of age). Compared interventions included cast immobilization with and without pinning and both bridging and non-bridging external fixation devises. Cast immobilization duration spanned from 4 to 6 weeks. External fixation treatment duration spanned from 4 to 8 weeks. Length of follow up ranged from 4 months to 10 years. The quality of each trial's methodology was rated based on the Cochrane Handbook for Systematic Reviews of Interventions recommendations using the Cochrane Bone Joint and Muscle Trauma Group quality assessment tool (Higgins & Green, 2006). Ratings were disappointing for the majority of the trials due to systematic biases, leading to concerns about their internal and external validities.

Young et al. (2003) and Kreder et al. (2006) are two trials reviewed in the Handoll et al. (2007) systematic review that had the best methodological quality. Both studies included independent evaluators as a form of blinding during outcome assessment, patient randomization with a clear description of subject allocation concealment, description of sufficient inclusion and exclusion criteria, and validated functional outcome measures.

In Young et al.'s (2003) study, 125 patients with dorsally displaced DRFs were randomly assigned to a 6-

week bridging external fixation or below-elbow plaster immobilization treatment. Both treatment groups were prospectively assessed during immobilization on a weekly basis; and then at 3, 6, 12 months; and 7 years. Outcome measures were radiographic parameters, wrist active ROM, grip strength, patient satisfaction, and function via the Gartland and Werley (1951) scale. Due to 31% subject attrition, only 86 subjects were available for a 7-year assessment.

Results of the Young et al. (2003) study showed no significant differences between groups on wrist active ROM and grip strength at all assessment times. The external fixation treatment group had significantly better radiographic findings in terms of radial shortening and radial angulation across all assessment times. There was a high rate of fracture malunion (51%) for both groups. The external fixation treatment was significantly better, having one third less malunion cases. There were no long-term differences in pain and function between the groups at 7 years. The functional outcome was rated as good or excellent in 94% of all cases in each group. Pain-free status was reported in 83 and 78% of the external fixation and cast immobilization subjects, respectively.

Young et al. (2003) reported no significant difference in post-traumatic arthritis between groups at

7 years with an overall incidence of 14% when DRF was classified to be intra-articular. One significant complication for the external fixation group was the high incident (36%) of forearm incision hypersensitivity. In spite that both treatments resulted in equivalent long-term functional results and patient satisfaction, the authors concluded that the external fixation treatment offered better fracture stabilization as per radiographic results.

In the Kreder et al. (2006) study, 113 patients with dorsally displaced extra-articular DRFs were randomly assigned to 6 to 8 weeks of bridging external fixation or above-elbow plaster immobilization treatment after closed reduction. The external fixation treatment was combined with Kirschner pins in 19 patients that needed further stabilizion of their distal radial fragment. Both treatment groups were assessed at 6 weeks, 6 months, and 1 and 2 years post treatment. The primary outcome measures were radiographic parameters, the Musculoskeletal Function Assessment, and SF-36 questionnaire. Secondary outcomes measures were the Jebsen-Taylor Hand Function Test, grip and pinch strength, wrist and digital active ROMs and a sensory exam. Due to 25% subject attrition, only 85 subjects were available for the 2-year assessment.

Results of the Kreder et al. (2006) study showed that all DRFs were fully healed at 6 months with no significant difference between the groups. No significant differences on the primary and secondary outcomes existed between the groups across all assessment times. At the 2-year assessment, there was a clear trend for better functional, clinical, and radiologic outcomes among the patients treated in the external fixation treatment group. Although this difference was not statistically significant, the authors attributed this finding to their small sample size available at the 2-year assessment. Approximately 9% of DRFs treated with cast immobilization required re-manipulation due to loss of fracture reduction within the first 6 weeks of treatment. No re-manipulations were needed in the external fixation with pinning group. Other treatment complications included 6 cases of pin site infections and 1 case of reflex sympathetic dystrophy in the external fixator group. It was concluded that both treatments were equally effective for treating displaced extra-articular DRFs, with the combination of external fixator and pinning having better radiographic outcomes.

Although both of the aforementioned trials were selected due to the quality of their methodology, they have limitations in their methodologies. The Gartland and Werley scale (1951), which was used in Young et al.

(2003) study, lacks validation as a functional outcome tool. Similarly, the Jebsen-Taylor Hand Function Test, which was used in Kreder et al. (2006) study, has been determined by Sears and Chung (2010) to have poor validity, responsiveness, and sensitivity when applied to surgically-treated hand patients, including those with DRFs. Both studies can also be criticized for their long-term patient attrition.

The final conclusion of the Handol et al. (2007) systematic review was in agreement with the conclusion of the Young et al. (2003), Kreder et al. (2006) as well as the previous systematic review by Handol and Madhok (2003a). There is some evidence to support the efficacy of external fixators for maintaining better fracture stability and preventing fracture redisplacement and malunion when compared to cast immobilization for dorsally displaced DRFs. However, the evidence for improved short- and long-term function after external fixation treatment is weak. The better radiological outcomes in the external fixation treatment are contrasted by its reported higher complications of pin site infections and nerve irritation after treatment.

Two randomized prospective trials by Grewal, Perey, Wilmink, and Stothers (2005) as well as Kredel et al. (2005) compared ORIF with dorsal plating to augmented external fixation with pinning treatments. Such a

comparison was not included in the systematic review by Handoll and Madhok (2003a). In Grewal et al.'s study, 62 patients with unstable intra-articular DRFs were randomly assigned to one of two treatments: ORIF with dorsal plating and augmented external fixation with pinning. All patients were under 70 years of age (mean age was 45 years) and had DRFs with at least a 2 mm articular deformity. Both groups were comparable in terms of age, gender, hand dominance, fracture severity, mechanism of injury, and work compensation status. The ORIF treatment group was treated via a dorsal plate. Both groups were assessed at 2 weeks, 4 to 6 weeks, 10 to 12 weeks, 6 months, and 1 and 2 years post treatment. Outcome measures were wrist and hand active ROMs, grip and pinch strength, sensory status, visual analog pain score, DASH score, and radiographic parameters. In addition, the SF-36 was assessed at 1 and 2-year time periods.

Grewal et al. (2005) reported that grip strength was significantly better in the fixator group at the 2-year assessment time. The final active ROM as well as the DASH and SF-36 scores were not significantly different between the two groups. Although, the external fixator group had significantly greater pain levels than the ORIF group at 1 year, there was no significant difference in pain between the groups at 2 years. Final radiographic parameters between the two groups were similar except for

an ulnar-positive variance and carpal sag. The external fixator group had significantly greater ulnar-positive variance, while the ORIF group had a significantly greater degree of carpal sag.

The treatment groups differed in post treatment complication rates in the Grewal et al. (2005) study. This difference was statistically significant. The external fixator group presented an overall 24.2% complication rate that included cases of reflex sympathetic dystrophy, carpal joint instability, sensory loss, persistent hand stiffness, pin track infection, and painful ulnar wrist. The dorsal plate ORIF group presented an overall 72.4% complication rate that included reflex sympathetic dystrophy, sensory loss, extensor tendonitis, painful ulnar wrist, and need for hardware removal due to dorsal wrist pain.

Grewal et al. (2005) concluded that the external fixation treatment augmented with percutaneous pinning was a more effective treatment option with fewer complications than the dorsal plating. Treatment with a dorsal plate induced significantly greater soft tissue disruption with high complication rates. The authors projected that future DRF treatment with volar plating would be a promising replacement of the dorsal plating method. One methodological limitation in this study was the small sample size, which may have contributed to lack

of significant differences in functional outcomes between the two groups. Other limitations of this study included its lack of assigning an independent examiner and not blinding the assessors. The main strength of this study was the inclusion of validated functional scales.

Kredel et al. (2005) randomly assigned 179 patients with unstable intra-articular DRFs to ORIF or augmented external fixation with pinning treatment groups. The patient age range of each group was between 16 and 75 years, and all patients had DRFs with at least a 2 mm articular deformity. Both groups were comparable in terms of age, gender, hand dominance, fracture severity, and mechanism of injury. The ORIF treatment group was treated via both dorsal and volar plates based on surgeon discretion. Both groups were assessed at 6 and 12 months, and 2 years after treatment. Functional outcome measures were the Musculosceletal Functional Assessment and the SF-36 scale. Objective outcomes were wrist and the hand active ROMs, grip and pinch strength, the Jebsten-Taylor Hand Function Test, and radiographical parameters.

Results of the Kredel et al. (2005) study showed no significant difference in pain between the two groups beyond 6 weeks. The external fixator group had better scores in the Musculosceletal Functional Assessment at 6 months but no significant group difference existed for both the SF-36 and Musculosceletal Functional Assessments

beyond 6 months after treatment. Functional active wrist ROM was regained by 6 months in both groups, and there was no significant difference in active ROM and pinch strength between the groups throughout all assessment times. Grip strength was significantly better in the external fixator group only at the 6-month assessment time period.

Kredel et al. (2005) reported similar post treatment complication rates between the two groups. These included 6 and 2% surgery site infections for the external fixation and ORIF groups, respectively. Reflex sympathetic dystrophy occurred in 1 and 3 patients in the external fixation and ORIF groups, respectively. Although the extensor tendon tenosynovitis incidence was not mentioned, no cases of extensor tendon rupture that required surgical repair were reported. The incidence of intra-articular deformity after union was identical in both groups (14%). There was no significant difference between the groups in the incidence of osteoarthritis with 7 and 6 cases in the external fixation and ORIF groups, respectively.

The results of Kredel et al. (2005) study do not support the superiority of either treatment type. The authors reported that the external fixator group showed faster functional recovery at 6 months, which they attributed to less tissue dissection and damage as

compared to ORIF. However, this result could have been influenced by methodological flaws such as using a non-validated functional scale (Musculosceletal Functional Assessment) and treatment group heterogeneity, as well as high patient attrition levels of 22 and 34% at 1 and 2 years, respectively. No statistical data on treatment outcomes were provided for plate comparisons within the ORIF group.

The first study to compare volar to dorsal ORIF surgical treatment approaches for DRFs was reported by Rush and Papadonikolakis (2006). In this study, data from 34 patients with unstable intra-articular DRFs who underwent ORIF via either dorsal or volar non-locking plate techniques were reviewed retrospectively. The dorsal approach group consisted of 20 DRF patients (49 year mean age). The volar approach group consisted of 14 patients (46 year mean age). The same surgeon was used for both groups. Surgical approach selection was based on the direction (volar or dorsal) of the DRF displacement as well as surgeon preference. A 6-week cast immobilization was used post operatively for both groups. Functional outcomes were measured via the DASH and Gartland and Werley scales. Objective outcomes were radiographic parameters, active ROM, and grip strength.

The results of Rush and Papadonikolakis (2006) study indicated no significant difference between treatment

groups in DASH scores, grip strength, and active ROM. The volar plating approach had significantly better Gartland and Werley Scale scores. Based on this scale, final surgery outcomes were rated good or excellent in 85 and 75% cases in the volar and dorsal plating treatment groups, respectively. All DRFs reached full healing with no evidence of nonunion. Complications occurred significantly more frequently in the dorsal plating treatment group than in the volar plating treatment group. The most frequent complications in the dorsal plating treatment group were volar fragment collapse and extensor tendon tenosynovitis or rupture. In the volar plating treatment group the most frequent complication was median nerve compression.

The Rush and Papadonikolakis (2006) study has methodological limitations as well. Their conclusion that volar plating treatment is a superior surgical treatment for DRFs is difficult to generalize since it was based on the Gartland and Werley (1951) scale only, which is not a function validated instrument. Its main objective is to score DRF surgical outcomes on objective measures only such as bony deformity, pain, wrist active ROM, and complication rates. Such parameters do not reflect any element of patient function as described by the ICF model. This study’s small sample size and retrospective analysis further decreased the confidence of its results.

Wei et al. (2009) conducted a prospective clinical trial in which 46 patients with unstable DRFs were randomly assigned to external fixation augmented with pin fixation, volar or dorsal ORIF plating surgical groups. The patient mean age was 55, 60, and 61 years for each of the three aforementioned treatment groups, respectively. All groups were comparable in terms of age, gender, hand dominance, fracture severity, and mechanism of injury. All groups were assessed at 6 weeks; and 3, 6, and 12 months after treatment. The main functional outcome measure was the DASH questionnaire. Objective outcome measures were pain, wrist active ROMs, grip and key pinch strength, and radiographical parameters. Assessment blinding was enforced via the use of an independent investigator who completed all objective and functional outcome measurements.

Results of the Wei et al. (2009) study indicated that at 6 weeks post treatment both the volar and dorsal plating treatments had significantly better DASH scores than the external fixator group. At 3 months the volar plate treatment was significantly superior to both dorsal plate and external fixator treatment methods in DASH scores. At 6 months all treatments had comparable functional outcomes. At 1 year the volar plate treatment group showed significantly better functional scores than the dorsal plate and external fixator methods. All

treatment groups showed significant functional improvement in DASH scores as compared to their initial disability levels before treatment. Significant difference in grip strength was observed only at 6 months with the volar plate and external fixator groups being superior to dorsal plate group. No other significant differences between treatment groups were observed on objective measurements across all assessment times. At 1 year all treatment groups had significantly improved objective measurements as compared to their initial levels, and wrist active ROM reached functional levels in all treatment groups.

Radiographic results of the Wei et al. (2009) study indicated that the dorsal plate was significantly better than the volar plate and external fixator treatments in maintaining better radial inclination and radial length in all assessment times. No significant differences between the treatment groups in palmar tilt, ulnar variance, and intra-articular deformity were observed across all assessment times. The majority of patients had uncomplicated treatments (83%) and no significant differences in post-treatment complications were observed between groups. The generalization of this study’s results is positively reinforced by its strong study methodology and 80% power to detect difference in functional scores at 1 year.

Egol et al. (2008) conducted a prospective trial in which 88 patients with unstable DRFs were randomly assigned to an external fixation augmented with pin fixation or a volar plating treatment group. The mean patient age was 49 and 52 years for the two treatment groups, respectively. Both groups were comparable in age, gender, hand dominance, fracture severity, socio-economic status, and health co-morbidities. Patients were assessed clinically and radiologically at 2 and 6 weeks; and 3, 6, and 12 months after surgery. Clinical assessment measurements consisted of pain, wrist active ROM, grip strength, and functional outcome on the DASH questionnaire. Short-term (up to 6 months) results indicated that DRF patients treated with a volar plate required significantly less physical therapy to reach functional recovery and had significantly better wrist AROM and radiographic outcomes than those treated with an external fixator. These short-term differences were fully offset by 12 months when both treatment groups had comparable long-term outcomes in all radiographic parameters, clinical measurements, and post-surgical complications. This study’s results concurred with the Wei et al. (2009) study conclusion.

Rozenthal et al. (2009) conducted a prospective clinical trial in which 45 patients with unstable DRFs were randomly assigned to closed reduction with

percutaneous pin fixation and 6 weeks cast immobilization or ORIF with a locking volar plate technique. The patient mean age was 52 and 51 years for the two treatment groups, respectively. All groups were comparable in terms of age, gender, hand dominance, and fracture severity. All groups were assessed at 7 and 10 days, 6 and 9 weeks, 3 and 12 months after treatment. The main functional outcome measure was the DASH questionnaire. Objective outcome measures were pain, digital and wrist active ROMs, grip and key pinch strength, and radiographical parameters. Both treatment groups were assessed by a blinded independent investigator who collected all objective and functional outcomes.

Results of the Rozenthal et al. (2009) study indicated that the volar plating ORIF treatment had significantly better DASH scores, wrist and digital active ROMs, grip and pinch strength values than the closed reduction with pinning and immobilization group at 7 to 10 days post operative time periods. The same trend continued at 6 and 9 weeks except for digital active ROM which was comparable for both groups. At 3 months no significant differences existed between treatment groups on all outcome measures, except for functional DASH scores, which remained significantly better in the volar plating ORIF treatment group. At 12 months both treatment

groups were comparable in both objective and functional outcome scores.

Radiographic results of the Rozenthal et al. (2009) study indicated that both treatment groups were comparable in adequate fracture reductions, with no incidence of fracture malunion. Both treatment groups had comparable early post-operative results at 7 to 10 days in radial height, radial inclination, and palmar tilt. At 12 months these radiological indicators were essentially unchanged. All fractures reached complete union at 6 weeks for both groups. Post-operative complication rate was 8% in the volar platting group and 27% in the closed reduction with percutaneous pin fixation group. This study's results are positively reinforced by its strong study methodology, low attrition levels (6%), and 80% reported power to detect difference in functional scores at 1 year. The two main limitations in this study consist of the differences in volar plate selection among surgeons and the exclusion of patients with complex intra-articular DRFs.

Leung, Tu, Chew, and Chow (2008) conducted a prospective multi-center clinical trial to determine the most effective treatment method for the more complex intra-articular DRFs. In this study, 144 DRF patients were randomly assigned to external fixation with percutaneous pin fixation augmentation or ORIF with a

dorsal, volar or both plate techniques. Both treatment groups were comparable in terms of age, gender, hand dominance, and fracture severity. All groups were assessed clinically (i.e., Gartland and Werley scale) and radiographicaly at 7 days; and 6, 12, and 24 months following surgery.

The Leung et al. (2008) study results indicated a significant superiority of the ORIF plating treatment method in all clinical scores, radiographic assessment, and post-operative complications across all assessment times. Methodological limitations of this study consisted of not blinding the assessors; use of the Gartland and Werley scale, which is not a function validated scoring system; not comparing outcomes between the different ORIF plating methods used; and having large patient attrition (29%) at 24 months, which led to inadequate statistical power. Clinical generalization of this study’s results is convincingly hindered by these methodological flaws.

Diaz-Garcia, Oda, Shauver, and Chung (2011) conducted the latest systematic review to determine the most updated evidence on DRF management via a volar locking plate, non-bridging and bridging external fixator, percutaneous pinning, and cast immoblization. Inclusion criteria were met by 21 articles. These articles consisted of 8 randomized control trials, 3 prospective cohort studies, and 10 retrospective case

series published between 1980 and 2009, involving 1,010 adult DRF patients (60 years of age and over) who were assessed up to 12 months post treatment on radiographic outcomes, objective parameters (i.e., wrist AROM, grip strength) and patient-rated functional outcomes using the DASH scale. The quality of each trial's methodology was rated based on the Structured Effectiveness Quality Evaluation Scale (MacDermid, Walton, & law, 2009) and Sackett's level of evidence (Sackett, Strays, Richardson, Rosenberg, & Haynes, 2000). The Structured Effectiveness Quality Evaluation Scale appraises the overall quality of a study based on 24 individual criteria associated with study design, subject accrual, intervention, outcomes, analysis, and recommendations. Each criterion is scored in a 0 to 2 scale. The summation of all 24 scores represents the study's total quality score (MacDermid et al.). In the Diaz-Garcia et al. study 7 articles were rated of having high quality (33 to 48), 12 articles moderate quality (17 to 32) and 2 articles low quality (< 16) scores.

The results of Diaz-Garcia et al. (2011) study indicated no clinically significant difference between treatments in functional scores, grip strength, and active ROM after 12 months of patient recovery. The volar plating and non-bridging external fixator treatments had significantly better scores in radiographic parameters

(i.e., volar tilt and ulnar variance) than the bridging external fixator and the cast immobilization treatment, offering a better treatment option for unstable DRFs. This study's results are largly weakened by its methodological limitation to include lower evidence retrospective case series reports, very low proportion (9%) of studies that reported sufficient statistical power, and poor study homogenouity on fracture severity classification among treatments.

Currently, there is no single option that can be considered the gold standard for surgical treatment of all DRFs (Raia & Catalano, 2007). Primary decisions on surgical approach frequently depend on the surgeons experience and training, complication potential (Rosental Beredjiklian & Bozentka, 2003) and patient factors (Handoll & Madhok, 2003a). Other important factors are radiographic evidence of fracture severity (Handoll et al., 2007), and DRF fragment displacement direction (Rush & Papadonikolakis, 2006).

There is adequate evidence to support the benefit of treating unstable extra-articular DRFs via minimally invasive methods, such as pinning or external fixators when they are expected to re-displace if treated only conservatively. The increased complication rates of pin site infection, loss of fracture reduction, prolonged pain, and sensory deficits have led to declining

popularity of these treatment methods (Handoll & Madhok, 2003a; Simic & Weiland, 2003). When a minimal invasive treatment with pinning or external fixation devices is not a viable treatment option for a DRF, ORIF via volar plating is recommended (Raia & Catalano, 2007). Volar plating has been proven to be biomechanicaly superior to treatment with percutaneous pins, especially for the treatment of unstable dorsally displaced intra-articular DRFs (Knox, Ambrose, McCallister, & Trumble, 2007).

Although a large body of clinical research has provided weak evidence to support or refute the superiority of single use or combinations of many types of surgical techniques (Handoll et al., 2007), recent clinical trials have provided stronger evidence for the surgical DRF management via volar plating techniques (Egol et al., 2008; Rozenthal et al., 2009; Wei et al., 2009). Biomechanical advantages have been reported for both dorsal and volar plating techniques for DRF stability (Osada et al., 2003; Trease et al., 2005). However, the volar plating surgical method has been described to result in faster return to function (Egol et al.; Rozenthal et al.; Wei et al.) and lower complication rates as compared to the dorsal plating method, which presents higher risk for extensor tendon attrition and ruptures (Handoll et al.; Rozenthal et al.). Complication rates of the volar plating technique are reported to be

as low as 8% (Rozenthal et al.) or as high as 27%, which frequently include carpal tunnel syndrome as well as flexor and extensor tendon irritation (Arora et al., 2007).

The recent trend among experienced orthopedic hand surgeons is to select ORIF treatment for unstable DRFS more frequently than conservative methods, resulting in an increased health care financial burden (Chung, Shauver, Yin, 2011). Among all ORIF methods, volar fixed-angle locking plates technology has increasingly become the prefered surgical method among hand surgeons for treating DRF patients (Chung et al., 2006; Osada et al., 2003; Trease e al., 2005; Weninger et al., 2010). This trend is supported by good biomechanical research evidence (Liporace et al., 2005; Osada et al.), and recent clinical trials that support the promising advantage of volar plating technology with fewer complications due to less surgical trauma, offering superior fracture stability and leading to earlier functional return (Rozenthal et al., 2009; Wei et al., 2009) even for the most complex DRFs (Arora et al., 2007; Gardner et al., 2004; Liporace et al.; Weninger et al.). However, the available evidence from current randomized controlled trials has been inadequate to establish a strong consensus for the long-term treatment superiority on either volar or dorsal plating techniques. Thus,

additional high quality prospective randomized controlled trials are needed to advance the future of DRF surgical treatment.

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APPENDIX A
INFORMED CONSENT FORM

Title of research study: Responsiveness of The Active Wrist Joint Position Sense Test Following Distal Radius Fracture Intervention

Principal Investigator: **Michael Sitler, Ed.D., ATC, FNATA**
Temple University, Department of Kinesiology
114 Pearson Hall, N Broad St, Philadelphia, PA 19122

Research Coordinator: **Christos Karagiannopoulos, MPT, MEd, ATC, CHT**
Doctoral Student Temple University,
Department of Kinesiology
114 Pearson Hall, N Broad St, Philadelphia, PA 19122

Co-Investigators: **Carole Tucker, PT, PhD**
Temple University, Department of Physical Therapy
617 Jones Hall, 3307 N Broad St, Philadelphia, PA 199140

Susan Michlovitz, PT, PhD, CHT
Cayuga Hand therapy, 903 Hanshaw Rd, Ithaca, NY

Ryan Tierney, PhD, ATC
Temple University, Department of Kinesiology
114 Pearson Hall, N Broad St, Philadelphia, PA 19122

Why you are being invited to take part in a research study?

We invite you to take part in a research study because of your wrist (distal radius fracture) injury after your surgery or your immobilization period have ended. To be a participant in this study, you must meet certain requirements that include being 18 years of age or older, being referred by your doctor to have supervised physical therapy, having the ability to read and speak English, and having adequate wrist motion.

Who can I talk to?

If you have questions, concerns, or complaints, or think the research has hurt you, contact the research team coordinator Christos Karagiannopoulos, 1200 Manor Drive, Chalfont, PA, 18914, Tel: 267-495-2515, chriskaragian@comcast.net.
This research has been reviewed and approved by an Institutional Review Board. You may talk to them at (215) 707-3390 or e-mail them at: irb@temple.edu for any of the following:

- Your questions, concerns, or complaints are not being answered by the research team.
- You cannot reach the research team.
- You want to talk to someone besides the research team.
- You have questions about your rights as a research subject.
- You want to get information or provide input about this research.

Subject Initials: ____

Date: _____

DO NOT SIGN THIS FORM AFTER THIS DATE →

Why are we doing this research?

We are conducting this research to study the accuracy of the active wrist joint position sense test, which is used by clinicians to measure an individual's ability to reposition his/her wrist at a specific joint angle after a distal radius fracture treatment. We are also studying how the accuracy of this test can be affected by treatment and pain. Inability to move the wrist to a specific angle after this fracture has been linked to wrist coordination deficits and functional difficulties with activities of daily living. Very limited research has been done on this topic. Results from this study are intended to help clinicians evaluate for a wrist position sense deficit more effectively after distal radius fracture treatment as well as develop more effective rehabilitation methods.

How long will the research last?

We expect that you will be participating in this research study until you reach 12 weeks from the first day of your cast immobilization or surgical treatment.

How many people will be studied?

We expect about 40 people to participate in this research study, which is being conducted only in this physical therapy clinic and approved by your OrthopediCare physician. This is the same clinic participants will have physical therapy after their wrist fracture.

What happens if I say yes, I want to be in this research?

If you decide to participate in this study, you will read and sign this informed consent form and a HIPAA form. Following this, the study research coordinator, a certified hand therapist, will ask you a few questions and fill in a demographical information form to determine your final eligibility for the study. This will be followed by you completing two brief questionnaires. The first questionnaire contains only a single question about your perception on the change of your physical well-being since the first day of your fracture treatment. The second questionnaire will assess your current pain and function levels on 15 questions. Following this, your ability to accurately move your wrist into a specific angle with eyes closed will be tested with a plastic goniometer placed on your injured wrist and your arm supported on a treatment table.

You understand that this study is not part of your regular physical therapy, and involves only three evaluation sessions consisting of 10-15 minutes each. Answering the first questionnaire and performing the wrist joint position sense test will be performed as part of the study. Completing the second questionnaire will be part of your usual physical therapy evaluation process. All the study procedures will take place at the beginning of your regularly scheduled physical therapy visits. The first testing session will be completed during your first physical therapy visit. The second and third testing sessions will take place when you reach 8 and 12 weeks from the day you started your cast immobilization or had surgery. The normal course of your physical therapy will not be affected by your participation in this study. If you complete your rehabilitation prior to 12 weeks, you will be asked to return to physical therapy one time to complete your last testing section free of charge.

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What happens if I say no, I do not want to be in this research?

You may decide not to take part in the research and it will not be held against you. It will in no way affect your relationship with your physician or physical therapist.

What happens if I say yes, but I change my mind later?

You agree to take part in the research now and if you stop at any time, it will not be held against you. Again, it will in no way affect your relationship with your physician or physical therapist. If you stop participating in the research, already collected data may not be removed from the study database. You will be asked whether the investigator can use these data. If you agree, these data will be handled the same as research data.

Is there any way being in this study could be bad for me?

Your participation in this study requires your physician's approval. Participation in this study involves minimal risk to you. Moving your wrist into a specific angle with eyes closed may cause a mild and transient wrist discomfort, which should not be greater than the anticipated discomfort you will experience during your standard physical therapy evaluation following your fracture treatment.

What happens to the information we collect?

Efforts will be made to limit your personal information, including research study and medical records, to people who have a need to review this information. We cannot promise complete secrecy. For example, though the study team has put in safeguards to protect your information, there is always a potential risk of loss of confidentiality. To minimize risk, all documents and information pertaining to this study will be kept confidential in accordance with all applicable federal, state, and local laws and regulations. Organizations that may inspect and copy your information include the Temple University IRB; Health System, Inc. and its affiliates, and other representatives of these organizations; and the Office of Human Research Protections. You understand that we may publish the results of this research. However, we will keep your name and other identifying information confidential. Federal law provides additional protections of your personal information. Privacy interests of participants will be protected by signing a HIPAA form.

Can I be removed from the research without my permission?

The person in charge of the research study can remove you from the research study without your approval. This may occur if you fail to meet the inclusion requirements of this study before or during testing. You will be informed about any new information that may affect your health, welfare, or choice to stay in the research.

What else do I need to know?

If you sustain an injury as a result of your participation in this research study, the physician's fees and medical expenses that result will be billed to your insurance company or you in the usual manner. Other financial compensation (such as lost wages or pain and suffering) for such injuries is not routinely available. By signing this consent form, you are not waiving any

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of the legal rights that you otherwise would have as a participant in a research study. If you have questions about the study or a research-related injury, please contact the research coordinator Christos Karagiannopoulos at 267 495-2515 during regular hours.

Stipend/Reimbursement

You will receive no compensation for participating in this study

Your signature below indicates that:

- Someone has explained this research study to you.
- You freely volunteer to be in this research study.
- You can choose not to take part in this research study and it will not affect your care.
- You can agree to take part in this study now and later change your mind. Your decision to leave the study will not affect your care.
- You have been offered the opportunity to ask questions and all your questions have been answered.

Page 5 of 5

Signature Block for Capable Adult

Your signature documents your permission to take part in this research.

DO NOT SIGN THIS FORM AFTER THIS DATE → [ ]

Signature of subject	Date
Printed name of subject	
Signature of person obtaining consent	
Printed name of person obtaining consent	

APPENDIX B
HEALTH INSURANCE PORTABILITY AND ACCOUNTABILITY ACT FORM

Authorization to use and disclose personal health information for research at Temple University, Temple University Health System Affiliates, and Temple University Clinical Faculty Practice Plan

Information that will be collected from you and disclosed

During the course of this research study, which is described by title in the attached consent form and study-specific document, certain personal health information will be collected and disclosed to recipients identified in this document. It is important for you to know that your personal health information may identify you by name, address, telephone number, photograph, social security number, health plan number, and date of birth, dates relating to various tests and procedures, or other personally identifiable information. This information may be obtained from your medical records, physical examinations and procedures: (a) to determine if you are eligible to participate in the research study or (b) created as a result of your participation in the research study.

How your information will be used and to whom it will be disclosed

By signing this authorization form, you give Temple University, Temple University Health System affiliates, and Temple University Clinical Faculty Practice Plan, Temple University Institutional Review Board, and the investigator(s) named in the attached study-specific document, permission to use your personal health information and to disclose this information to the following recipients (as applicable): sponsor; sponsor's agents; governmental entities overseeing research in the United States and abroad, which may include in the United States, the Food and Drug Administration and the Department of Health and Human Services. It is important for you to know that the recipients, and their agents or representatives, will take all reasonable efforts to maintain your personal health information in confidence, and to use appropriate safeguards to prevent further use or disclosure by those not authorized to use or disclose your personal health information. However, once your health information is disclosed to the recipients, then your personal health information may no longer be protected by federal privacy laws and regulations and there is a potential for re-disclosure of this information. However, the laws of the Commonwealth of Pennsylvania or your state of residence may provide further privacy protection.

How you can access your information

You should know that you have the right to see and receive a copy of your personal health information that was collected from you during the research study for as long as this information is maintained by Temple University and the principal investigator. However, while the research study is in progress, you will not be able to access your personal health information in order to preserve the integrity of the research. You will be able to access this information when the study is completed. There may be associated charges for copying these materials.

How to revoke your authorization

You should also know that you can revoke your authorization to disclose your personal health information at any time by sending a written notice to the principal investigator and Temple University at the address listed in the attached study-specific document. Should you decide to revoke your authorization, Temple University and the principal investigator will stop collecting your study-related health information. In addition, Temple University and the principal investigator will stop using and disclosing your personal health information, except to the extent such information was collected prior to your revocation. For instance, Temple University, principal investigator, recipients, and their agents or representatives may use the information obtained before you revoked your authorization in order to preserve the scientific integrity of the research study.

Important notices

You will receive a signed copy of this authorization to acknowledge your approval for Temple University and the principal investigator to the release your personal health information. If you do not sign this authorization or if you revoke this authorization, the principal investigator and Temple University cannot allow you to participate in or to continue to participate in the research study identified in the attached study-specific document.

STUDY-SPECIFIC DOCUMENT

1. RESEARCH STUDY: Responsiveness of The Active Wrist Joint Position Sense Test Following Distal Radius Fracture Intervention.

2. PRINCIPAL INVESTIGATOR: Michael Sitler, EdD, ATC, FNATA

3. **EXPIRATION DATE**: This Authorization does not expire.

Signature of Subject Date

Printed Name of Subject

Signature of Personal Representative of the Subject Date

Printed Name of Personal Representative of the Patient and Relationship to Subject

---

Signature of Person Collecting Authorization Date

Printed Name of Person Collecting Authorization

APPENDIX C
PARTICIPANT DEMOGRAPHIC AND CHARACTERISTICS FORM

College of Health Professions
TEMPLE UNIVERSITY

Department of Kinesiology
Pearson Hall (048-00)
Philadelphia, Pennsylvania,19122

Participant Demographic and Characteristics Form

Participant #: ____ Physicians Name: _____ Date: _____

Gender: □ Male □ Female Age: _____

Injury Side: □ Right □ Left DOI: _____

Dominant Side: □ Right □ Left (Side used to write)

Pain level (PRWE sub scale): □ Low (< 35) □ High (≥ 35)

Surgical Treatment: □ Volar Plate □ Dorsal Plate □ Ext. Fixator

DOS: _____ □ Percutaneous Pins □ Other _____

Non-Surgical Treatment: Start date: _____ □ closed reduction

Type of Immobilization: □ Plaster Cast □ Orthosis □ Both

Length of immobilization: _____ Date of cast removal: _____

Physical Therapy:

Start date: _____ Baseline assessment date: _____

8-Week assessment date: _____

12-week assessment date: _____

Total # of weeks in physical therapy: _____

APPENDIX D
PARTICIPANT SCREENER FORM

College of Health Professions
TEMPLE UNIVERSITY

Department of Kinesiology
Pearson Hall (048-00)
Philadelphia, Pennsylvania,19122

Participant Screener Form

Participant #: _____ Date: _____

Exclusion Criteria	Yes	No
Diagnosed with carpal tunnel syndrome presently		
Neurological pathologies resulting in paralysis or paresis of the involved upper extremity		
Rheumatoid disease in the involved wrist or hand		
Cognitive impairment that prevents the patient from following instructions safely		
Concomitant ipsilateral extremity injury or fracture within last 6 months		
Concomitant ulna fracture as a result of the current DRF injury		
Ipsilateral upper extremity lymphedema that affects wrist and hand motion		
Blindness		
Pregnancy		
Extended length of immobilization that does not permit testing at 8 weeks following fracture treatment		

APPENDIX E
DATA COLLECTION FORM

College of Health Professions
TEMPLE UNIVERSITY

Department of Kinesiology
Pearson Hall (048-00)
Philadelphia, Pennsylvania, 19122

Data Collection Form

ACTIVE WRIST JPS TEST

Patient #: _____ Date: _____

1. Initial Assessment:

20º Wrist Extension	Trial 1	Trial 2	Mean
R wrist			
L wrist			

2. At 8 weeks:

20º Wrist Extension	Trial 1	Trial 2	Mean
R wrist			
L wrist			

3. At 12 weeks:

20º Wrist Extension	Trial 1	Trial 2	Mean
R wrist			
L wrist			

APPENDIX F
PATIENT’S GLOBAL IMPRESSION OF CHANGE SCALE

College of Health Professions
TEMPLE UNIVERSITY

Department of Kinesiology
Pearson Hall (048-00)
Philadelphia, Pennsylvania, 19122

PATIENT'S GLOBAL IMPRESSION OF CHANGE SCALE

Patient #_____ Date: _____

Initial Assessment: ___ 8 weeks: ___ 12 weeks: ___

Question:

Since the start of your fracture treatment (surgery or immobilization) how would you describe the change (if any) in ACTIVITY LIMITATION, SYMPTOMS, EMOTIONS AND OVERALL QUALITY OF LIFE, related to your painful wrist injury?

Please circle the number below that matches your degree of change since beginning care at this clinic for the above stated chief complaint.

No change	Almost the same	A little better	Somewhat better	Moderately better	Better	A great deal better
1	2	3	4	5	6	7

Explanation:

1 = No change (or condition has got worse)
2 = Almost the same, hardly any change at all
3 = A little better, but no noticeable change
4 = Somewhat better, but the change has not made any real difference
5 = Moderately better, and a slight but noticeable change a real and worthwhile difference
6 = Better, and a definite improvement that has made a real and worthwhile difference
7 = A great deal better, and a considerable improvement that has made all the difference

APPENDIX G
PATIENT-RATED WRIST EVALUATION

PATIENT RATED WRIST EVALUATION

Name_____ Date_____

The questions below will help us understand how much difficulty you have had with your wrist in the past week. You will be describing your average wrist symptoms over the past week on a scale of 0-10. **Please try to provide an answer for ALL questions.** If you did not perform the activity in the past week, please ESTIMATE the usual pain or difficulty you would expect. If you have never performed the activity you may leave it blank.

1. PAIN

Rate the average amount of pain in your wrist over the past week by circling the number that best describes your pain on a scale from 0-10. A zero (0) means that you did not have any pain and a ten (10) means that you had the worst pain you have ever experienced or that you could not do the activity because of pain.

Sample scale → 0 1 2 3 4 5 6 7 8 9 10
No Pain Worst Ever

RATE YOUR PAIN:	
At rest	0 1 2 3 4 5 6 7 8 9 10
When doing a task with a repeated wrist movement	0 1 2 3 4 5 6 7 8 9 10
When lifting a heavy object	0 1 2 3 4 5 6 7 8 9 10
When it is at its worst	0 1 2 3 4 5 6 7 8 9 10

How often do you have pain? 0 1 2 3 4 5 6 7 8 9 10
Never Always

2. FUNCTION

A. SPECIFIC ACTIVITIES

*Rate the **amount of difficulty** you experienced performing each of the items listed below, over the past week, by circling the number that describes your difficulty on a scale of 0-10. A zero (0) means you did not experience any difficulty and a ten (10) means it was so difficult you were unable to do it at all.*

Sample scale → 0 1 2 3 4 5 6 7 8 9 10
No Difficulty Unable To Do

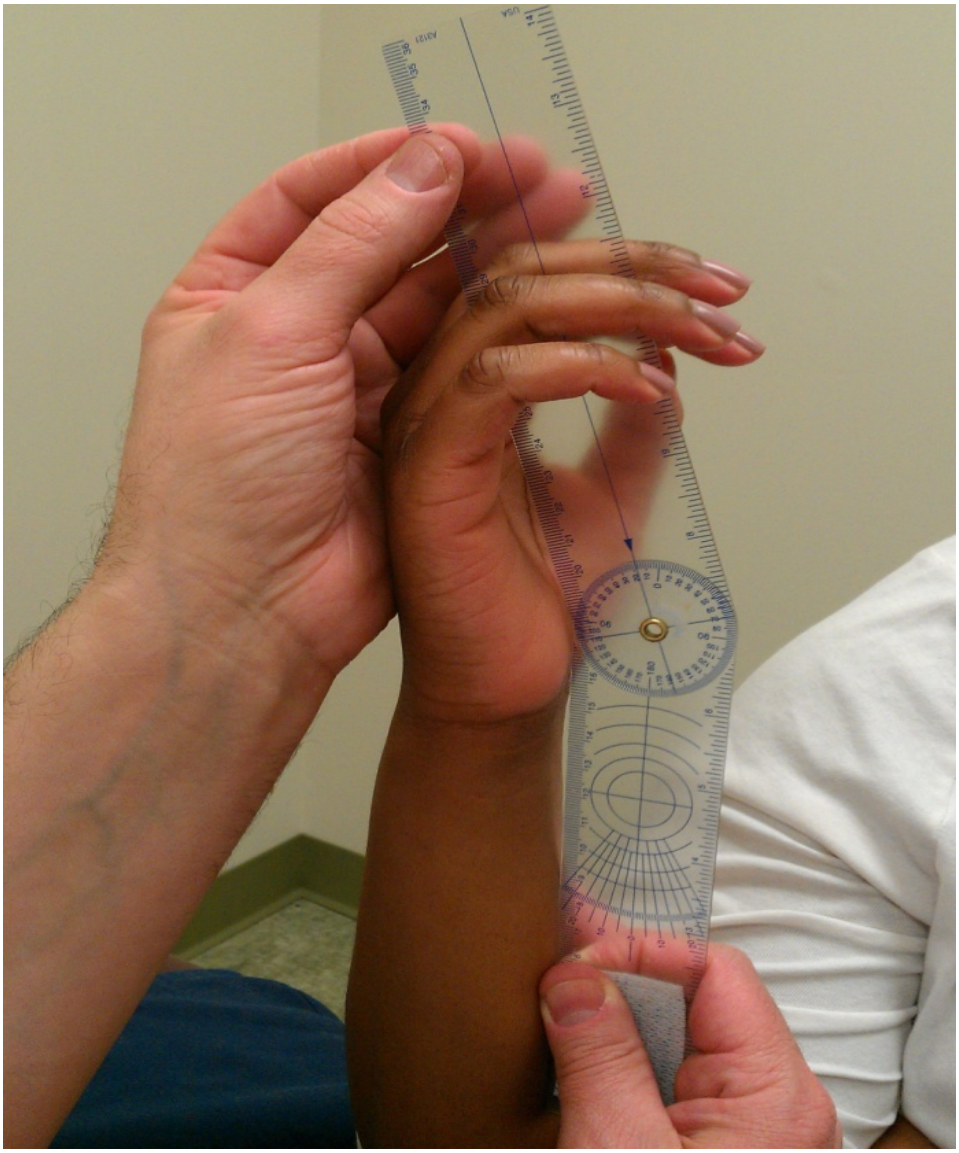
Turn a door knob using my affected hand	0 1 2 3 4 5 6 7 8 9 10
Cut meat using a knife in my affected hand	0 1 2 3 4 5 6 7 8 9 10
Fasten buttons on my shirt	0 1 2 3 4 5 6 7 8 9 10
Use my affected hand to push up from a chair	0 1 2 3 4 5 6 7 8 9 10
Carry a 10lb object in my affected hand	0 1 2 3 4 5 6 7 8 9 10
Use bathroom tissue with my affected hand	0 1 2 3 4 5 6 7 8 9 10

B. USUAL ACTIVITIES

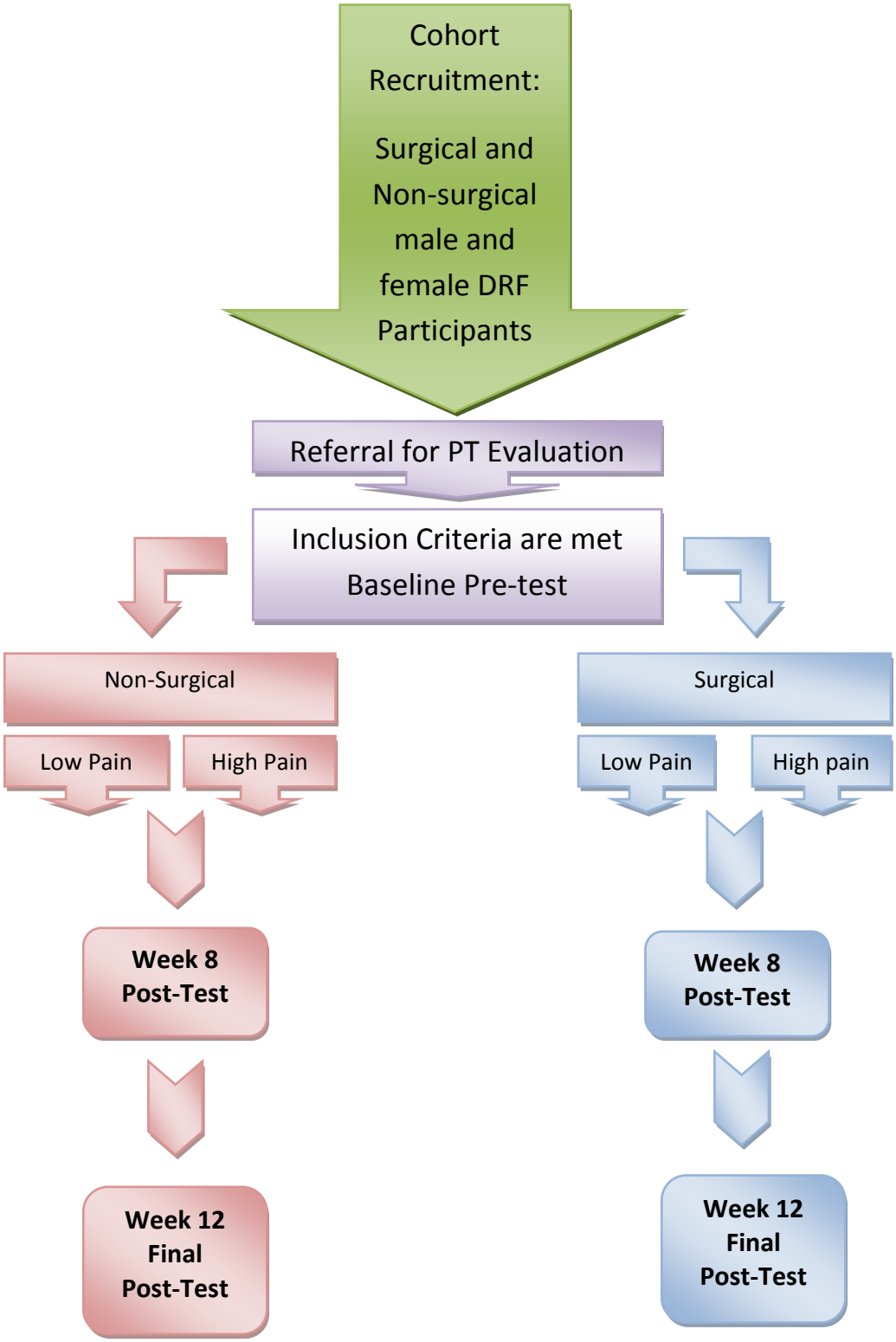
*Rate the **amount of difficulty** you experienced performing your usual activities in each of the areas listed below, over the pat week, by circling the number that best describes your difficulty on a scale of 0-10. By "usual activities", we mean the activities you performed before you started having a problem with your wrist. A zero (0) means that you did not experience any difficulty and a ten (10) means it was so difficult you were unable to do any of you usual activities.*

1. Personal care activities (dressing, washing)	0 1 2 3 4 5 6 7 8 9 10
2. Household work (cleaning, maintenance)	0 1 2 3 4 5 6 7 8 9 10
3. Work (your job or usual everyday work)	0 1 2 3 4 5 6 7 8 9 10
4. Recreational activities	0 1 2 3 4 5 6 7 8 9 10

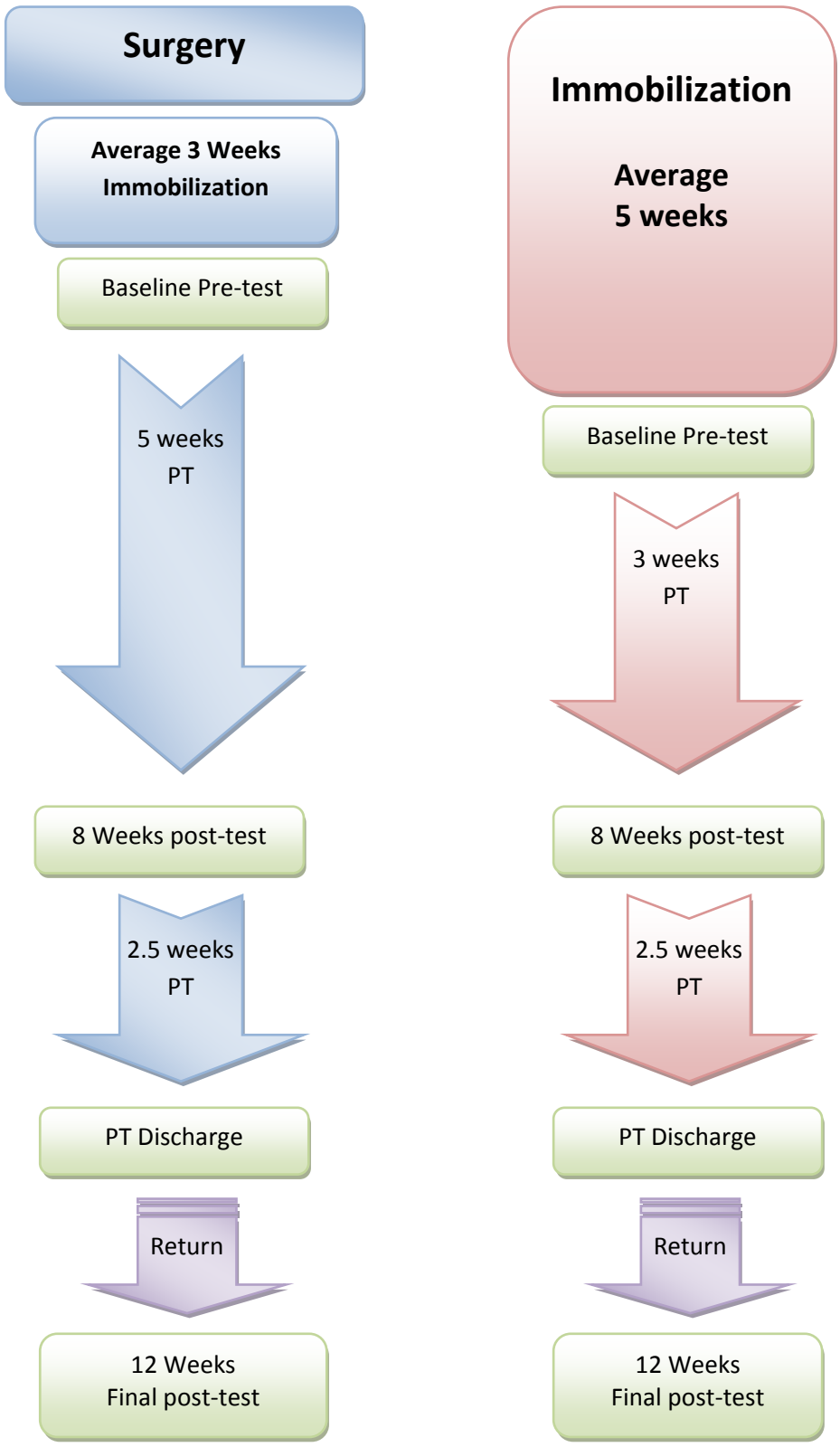
APPENDIX H
ACTIVE WRIST JOINT POSITION SENSE TEST



APPENDIX I
STUDY DESIGN


Cohort Recruitment:
Surgical and Non-surgical male and female DRF Participants
Referral for PT Evaluation
Inclusion Criteria are met
Baseline Pre-test
Non-Surgical
Low Pain
High Pain
Surgical
Low Pain
High pain
Week 8 Post-Test
Week 8 Post-Test
Week 12 Final Post-Test
Week 12 Final Post-Test

APPENDIX J
TREATMENT AND TESTING TIMELINE


Surgery
Average 3 Weeks Immobilization
Baseline Pre-test
5 weeks PT
8 Weeks post-test
2.5 weeks PT
PT Discharge
Return
12 Weeks Final post-test
Immobilization
Average 5 weeks
Baseline Pre-test
3 weeks PT
8 Weeks post-test
2.5 weeks PT
PT Discharge
Return
12 Weeks Final post-test

APPENDIX K
INSTRUMENT RESPONSIVENESS DEFINITION, STUDY PRIMARY AND SECONDARY AIMS AND THEIR STATISTICAL ANALYSES

Table K-1. Study Primary Aim, Instrument Responsiveness Definition, and Types of Responsiveness Statistical Indices and Analyses

Primary Aim:	To determine responsiveness of the active wrist JPS test.
Responsiveness:	Ability to detect wrist sensori-motor deficit change when it has occurred.

Statistical Indices	Characteristics	Statistical Analysis	Calculations
Group-Based:			
ES	Scale-based	Distribution-based	Mean score change/Initial Score SD
SRM	Scale-based	Distribution-based	Mean score change/SD score change
Individual-based:			
MDC	Instrument-based	Distribution-based	$MDC = Z * SEM * \sqrt{2}$
MCID	Focus on Person Perspective	Anchor-based	Mean score change in JPS test linked to PGIC scale score (≥ 6 points)

Note. ES = Effect Size, SRM = Standardized Response Mean, MDC = Minimum Detectable Change, MCID = Minimum Clinical Important Difference, SEM = Standard Error of Measurement, Z = Z-Score, JPS = Joint Position Sense, and PGIC = Patient’s Global Impression of Change Scale.

Table K-2. Study Secondary Aims and Their Statistical Analyses

Secondary Aims	Statistics	Analysis
1. To determine if difference exists between non-surgical and surgical DRF interventions on the active wrist JPS test responsiveness.	1-Factor ANCOVA	MCID Group Main Effect
2. To determine if difference exists between high- and low-pain level participants following DRF intervention on the active wrist JPS test score and responsiveness.	1-Factor ANCOVA T-Test (Bonferroni Cor.)	MCID, Act. Wrist JPS Test Pain Main Effect
3. To determine the relationships between Active wrist JPS test MCID and Function	Pearson Correlations 1-Factor Rep-Meas ANOVA	MCID Composite PRWE Score Collapsed Data
4. To determine the PGIC scale intra-tester reliability for assessing global health status change following DRF intervention.	ICC Statistics Model 3	PGIC 2 Trials Baseline Testing

Note. ANCOVA = Analysis of Covariance, MCID = Minimum Clinical Important Difference, JPS = Joint Position Sense, PGIC = Patient’s Global Impression of Change Scale, PRWE = Patient-Rated Wrist Evaluation, Bonferroni Cor. = Bonferroni Correction, Act. = Active, Rep-Meas ANOVA = Repeated Measures Analysis of Variance, and ICC = Inter-class Correlation Coefficient.

APPENDIX L
PARTICIPANTS' RAW DATA

Table L-1. Surgical Participants Raw data

Surgical Participant Number	Pain Level	Age	Gender	HDom	PTWks	PTVis	Immob	PRWE1	PRWE8	PRWE12
1	1.0	39.0	2.0	1.0	10.0	6.0	1.0	48.0	14.5	2.5
2	1.0	55.0	1.0	1.0	6.0	6.0	6.0	36.5	27.5	2.0
3	2.0	25.0	1.0	1.0	9.0	12.0	2.0	75.5	36.5	18.5
4	2.0	64.0	1.0	1.0	7.0	5.0	1.5	74.5	26.0	10.0
5	2.0	71.0	2.0	1.0	10.0	18.0	2.0	73.5	35.0	23.0
6	2.0	61.0	1.0	1.0	8.0	22.0	5.0	82.0	58.0	51.0
7	1.0	58.0	1.0	2.0	2.0	4.0	5.0	53.0	31.5	2.0
8	2.0	58.0	1.0	1.0	9.0	18.0	5.0	60.5	38.0	29.5
9	1.0	61.0	1.0	1.0	8.0	18.0	4.0	52.0	45.5	32.0
10	1.0	57.0	1.0	1.0	4.0	5.0	1.5	53.5	24.0	11.0
11	2.0	52.0	1.0	1.0	10.0	26.0	2.0	77.0	34.5	18.5
12	1.0	53.0	1.0	1.0	6.5	9.0	2.0	54.5	16.5	4.0
13	2.0	56.0	1.0	1.0	10.0	17.0	2.0	79.5	31.0	5.0
14	2.0	56.0	1.0	1.0	6.0	13.0	6.0	66.5	39.5	25.5
15	1.0	90.0	1.0	1.0	7.0	14.0	2.5	33.0	28.5	13.5
16	2.0	75.0	1.0	1.0	6.0	11.0	2.0	75.0	19.5	7.0
17	1.0	38.0	1.0	1.0	7.0	14.0	4.0	54.5	34.5	16.0
18	1.0	64.0	1.0	1.0	8.0	22.0	5.0	76.5	57.5	38.0
19	1.0	60.0	2.0	1.0	8.0	13.0	2.0	46.0	10.5	4.0
20	2.0	76.0	1.0	2.0	6.5	20.0	6.0	84.5	56.5	35.0

Note: Pain Level 1 = Low, Pain Level 2 = High, Gender 1 = Female, Gender 2 = Male, HDom 1 = Right Hand Dominance, HDom 2 = Left Hand Dominance, PTWks = Physical Therapy Weeks, PTVis = Physical Therapy Visits, Immob = Immobilization in Weeks, PRWE1 = Patient Rated Wrist Evaluation at Baseline, PRWE8 = Patient Rated Wrist Evaluation at 8 Weeks, and PRWE12 = Patient Rated Wrist Evaluation at 12 Weeks.

Table L-1. (Continued)

Surgical Participant Number	PGIC 1a	PGIC 1b	JPST 1	PGIC 8	JPST 8	MCID 8	PGIC 12	JPST 12	MCID 12
1	4.0	4.0	13.0	6.0	8.0	5.0	7.0	2.0	11.0
2	4.0	4.0	9.0	6.0	7.0	2.0	7.0	2.0	7.0
3	4.0	4.0	7.0	5.0	5.0	0.0	6.0	3.0	4.0
4	4.0	4.0	8.0	6.0	3.0	5.0	7.0	1.0	7.0
5	5.0	5.0	18.0	6.0	10.0	8.0	7.0	5.0	13.0
6	3.0	3.0	10.0	5.0	8.0	0.0	6.0	6.0	4.0
7	4.0	4.0	18.0	7.0	5.0	13.0	7.0	3.0	15.0
8	3.0	3.0	11.0	6.0	7.0	4.0	6.0	6.0	5.0
9	5.0	5.0	11.0	6.0	7.0	4.0	7.0	3.0	8.0
10	5.0	5.0	11.0	6.0	3.0	8.0	7.0	2.0	9.0
11	3.0	3.0	10.0	5.0	3.0	0.0	6.0	3.0	7.0
12	5.0	5.0	8.0	7.0	5.0	3.0	7.0	5.0	3.0
13	4.0	4.0	12.0	7.0	6.0	6.0	7.0	4.0	8.0
14	5.0	5.0	8.0	6.0	8.0	0.0	6.0	4.0	4.0
15	5.0	5.0	9.0	6.0	6.0	3.0	7.0	4.0	5.0
16	5.0	5.0	14.0	6.0	3.0	11.0	7.0	2.0	12.0
17	5.0	5.0	9.0	7.0	3.0	6.0	7.0	2.0	7.0
18	4.0	4.0	11.0	5.0	6.0	0.0	6.0	2.0	9.0
19	4.0	4.0	11.0	6.0	5.0	6.0	7.0	5.0	6.0
20	5.0	5.0	9.0	5.0	7.0	0.0	6.0	7.0	2.0

Note: PGIC = Patient Global Impression of Change scale, JPST = Joint Position Sense Test, MCID = Minimal Clinically Important Difference, 1a = Baseline Trial 1, 1b = Baseline Trial 2, 1 = Baseline, 8 = 8 Weeks, and 12 = 12 Weeks.

Table L-2. Non-Surgical Participants Raw Data

Non-Surg Participant Number	Pain Level	Age	Gender	HDom	PTWks	PTVis	Immob	PRWE1	PRWE8	PRWE12
1	1.0	59.0	1.0	2.0	8.0	17.00	4.0	58.0	36.5	14.5
2	2.0	66.0	1.0	1.0	6.0	11.00	6.5	68.0	21.0	20.0
3	2.0	61.0	1.0	1.0	7.0	12.00	6.0	78.0	28.0	13.0
4	1.0	77.0	1.0	1.0	4.0	5.00	6.0	40.0	5.0	3.0
5	2.0	60.0	1.0	1.0	6.0	13.00	4.0	72.5	34.0	7.5
6	2.0	43.0	1.0	2.0	6.0	7.00	6.0	83.0	18.0	6.5
7	1.0	62.0	2.0	1.0	5.0	5.00	5.0	45.0	24.0	17.0
8	1.0	58.0	1.0	1.0	7.0	11.00	4.0	30.0	22.5	0.0
9	1.0	67.0	1.0	1.0	2.0	2.00	6.0	31.0	16.0	11.5
10	1.0	57.0	2.0	2.0	7.0	11.00	6.0	42.5	33.0	12.0
11	1.0	64.0	1.0	2.0	4.0	7.00	4.0	51.5	30.5	6.5
12	1.0	65.0	1.0	1.0	4.5	9.00	4.0	52.0	30.5	0.0
13	2.0	63.0	1.0	1.0	3.0	6.00	5.0	67.5	10.0	0.0

Note: Non-Surg = Non-Surgical, Pain Level 1 = Low, Pain Level 2 = High, Gender 1 = Female, Gender 2 = Male, HDom 1 = Right Hand Dominance, HDom 2 = Left Hand Dominance, PTWks = Physical Therapy Weeks, PTVis = Physical Therapy Visits, Immob = Immobilization in Weeks, PRWE1 = Patient Rated Wrist Evaluation at Baseline, PRWE8 = Patient Rated Wrist Evaluation at 8 Weeks, and PRWE12 = Patient Rated Wrist Evaluation at 12 Weeks.

Table L-2. (Continued)

Non-Surg Participant Number	PGIC 1a	PGIC 1b	JPST 1	PGIC 8	JPST 8	MCID 8	PGIC 12	JPST 12	MCID 12
1	4.0	4.0	6.0	6.0	3.0	3.0	6.0	2.0	4.0
2	3.0	4.0	18.0	6.0	12.0	6.0	7.0	3.0	15.0
3	4.0	4.0	12.0	5.0	9.0	0.0	6.0	7.0	5.0
4	5.0	5.0	9.0	7.0	8.0	1.0	7.0	5.0	4.0
5	2.0	3.0	15.0	6.0	10.0	5.0	7.0	10.0	5.0
6	4.0	4.0	12.0	6.0	10.0	2.0	7.0	4.0	8.0
7	5.0	5.0	11.0	6.0	4.0	7.0	7.0	2.0	9.0
8	5.0	5.0	11.0	7.0	3.0	8.0	7.0	3.0	8.0
9	5.0	5.0	12.0	6.0	7.0	5.0	7.0	3.0	9.0
10	4.0	4.0	8.0	5.0	7.0	0.0	7.0	1.0	7.0
11	5.0	5.0	8.0	6.0	5.0	3.0	7.0	5.0	3.0
12	5.0	5.0	9.0	6.0	4.0	5.0	7.0	4.0	5.0
13	5.0	5.0	11.0	7.0	10.0	1.0	7.0	6.0	5.0

Note: Non-Surg = Non-Surgical, PGIC = Patient Global Impression of Change scale, JPST = Joint Position Sense Test, MCID = Minimal Clinically Important Difference, 1a = Baseline Trial 1, 1b = Baseline Trial 2, 1 = Baseline, 8 = 8 Weeks, and 12 = 12 Weeks.

APPENDIX M
ANALYSIS OF COVARIANCE RESULTS FOR TREATMENT-TYPE AND PAIN-LEVEL GROUPS

Table M-1. Analysis of Covariance Test Results for Active Wrist JPS Test MCID Values for Treatment Type and Possible Covariates 8 Weeks Following DRF Treatment Intervention

Variable	MS	DF	F	Sig	Power
Independent					
Treatment	14.54	1	1.560	.230	.218
Error	9.54	21			
Covariates					
Dominance	5.89	1	.618	.440	.117
Age	3.30	1	.347	.562	.087
Gender	10.43	1	1.095	.307	.170

Note: JPS = Joint Position Sense, MCID = Minimal Clinically Important Deficit, DRF = Distal Radius Fracture, MS = Mean Square, DF = Degrees of Freedom, and Sig = Significance at ≤ .05.

Table M-2. Analysis of Covariance Test Results for Active Wrist JPS Test MCID Values for Treatment Type and Possible Covariates 12 Weeks Following DRF Treatment Intervention

Variable	MS	DF	F	Sig	Power
Independent					
Treatment	2.079	1	.182	.673	.070
Error	11.426	28			
Covariates					
Dominance	1.381	1	.121	.731	.063
Age	.513	1	.045	.834	.055
Gender	27.687	1	2.423	.131	.324

Note: JPS = Joint Position Sense, MCID = Minimal Clinically Important Deficit, DRF = Distal Radius Fracture, MS = Mean Square, DF = Degrees of Freedom, and Sig = Significance at ≤ .05.

Table M-3. Analysis of Covariance Test Results for Active Wrist JPS Test MCID Values for Pain Level and Possible Covariates 8 Weeks Following DRF Treatment Intervention

Variable	MS	DF	F	Sig	Power
Independent					
Pain Level	.072	1	.007	.934	.051
Error	10.219	21			
Covariates					
Dominance	1.736	1	.170	.684	.068
Age	1.350	1	.132	.720	.064
Gender	12.059	1	1.180	.290	.179

Note: JPS = Joint Position Sense, MCID = Minimal Clinically Important Deficit, DRF = Distal Radius Fracture, MS = Mean Square, DF = Degrees of Freedom, and Sig = Significance at ≤ .05.

Table M-4. Analysis of Covariance Test Results for Active Wrist JPS Test MCID Values for Pain Level and Possible Covariates 12 Weeks Following DRF Treatment Intervention

Variable	MS	DF	F	Sig	Power
Independent					
Pain Level	.101	1	.009	.926	.051
Error	11.497	28			
Covariates					
Dominance	2.469	1	.215	.647	.073
Age	.288	1	.025	.875	.053
Gender	26.934	1	2.343	.137	.315

Note: JPS = Joint Position Sense, MCID = Minimal Clinically Important Deficit, DRF = Distal Radius Fracture, MS = Mean Square, DF = Degrees of Freedom, and Sig = Significance at ≤ .05.

APPENDIX N
REPEATED MEASURE SINGLE-FACTOR ANALYSIS OF VARIANCE RESULTS FOR MINIMAL CLINICALLY IMPORTANT DIFFERENCE AND PATIENT-RATED WRIST EVALUATION

Table N-1. Repeated Measures Single Factor ANOVA Test Results for Active Wrist JPS Test MCID Value and Function (PRWE) for Baseline, 8 and 12 Weeks Following DRF Treatment Intervention

Independent Variables	MS	DF	F	Sig	P.Eta Sq	Power
MCID Value						
Treatment	160.74	1	46.86	.000	.594	1.00
Error	3.43	32				
PRWE						
Treatment	17997.23	2	194.09	.000	.858	1.00
Error	92.72	64				

Note: ANOVA = Analysis of Variance, JPS = Joint Position test, MCID = Minimal Clinically Important Difference, PRWE = patient-Rated Wrist Evaluation, DRF = Distal Radius Fracture, MS = Mean Square, DF = Degrees of Freedom, Sig = Significance at ≤ .05, and P. Eta Sq = Partial Eta Square.