QUADRICEPS STRENGTH PREDICTION EQUATIONS IN INDIVIDUALS WITH LIGAMENTOUS INJURIES, MENISCAL INJURIES AND/OR OSTEOARTHRITIS OF THE KNEE JOINT

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ATTESTATION OF AUTHORSHIP

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the qualification of any other degree or diploma of a university or other institution of higher leaning, except where due acknowledgment is made in the acknowledgments.

Signed ____________________________

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ABSTRACT

Objective: The objective of this study was to investigate the accuracy of eleven prediction equations and one prediction table when estimating isoinertial knee extension and leg press one repetition maximum (1-RM) performance in subjects with knee injuries and knee osteoarthritis.

Study Design: A descriptive quantitative research study was undertaken utilizing a cross-sectional design.

Background: Traumatic injuries and osteoarthritis are common musculoskeletal pathologies that can disrupt normal function of the knee joint. A frequent sequela of these pathologies is quadriceps femoris muscle weakness. Such weakness can contribute to disability and diminished levels of functional and recreational activity. Therefore, safe and accurate methods of measuring maximal strength are required to identify and quantify quadriceps strength deficits. One option proposed in the literature is the use of 1-RM prediction equations which estimate 1-RM performance from the number of repetitions completed with sub-maximal loads. These equations have been investigated previously using healthy populations and subjects with calf muscle injuries. However, to date, no known study has investigated their accuracy in individuals with joint pathologies.

Method: Machine-weight seated knee extension and seated leg press exercises were investigated in this study. Twenty subjects with knee injuries and 12 subjects with knee OA completed the testing procedures for the knee extension exercise. Nineteen subjects with knee injuries and 18 subjects with knee OA completed the testing procedures for the leg press exercise. All subjects attended the testing venue on three occasions. At the first visit a familiarization session was carried out. At the second and third visits each subject was randomly assigned to perform either actual or predicted 1-RM testing for both of the exercises. Twelve different prediction methods were used to estimate 1-RM performance from the results. The estimates of 1-RM strength were then compared to actual 1-RM performance to assess the level of

conformity between these measures. Statistical procedures including Bland and Altman analyses, intraclass correlation coefficients, typical error and total error of measurement were used in the analyses of the results. In addition, paired t-tests were performed to determine whether actual 1-RM values were significantly different across the control and affected limbs and whether there were any significant differences in predictive accuracy for each equation across the control and affected limbs. Finally, the number of subjects with predicted 1-RM values within 5% or less of their actual 1-RM values was determined for each equation.

Results: When the knee injury group performed the knee extension exercise, the Brown, Brzycki, Epley, Lander, Mayhew et al., Poliquin and Wathen prediction methods demonstrated the greatest levels of predictive accuracy. When two atypical subjects were identified and excluded from the analyses, the accuracy of these equations improved further. Following the removal of these two subjects, no significant differences in predictive accuracy were found for any of the equations across the affected and control limbs ($p > 0.05$). Typical errors and total errors were low for the more accurate prediction methods ranging from 2.4-2.8% and from 2.4-3.5%, respectively. Overall, the Poliquin table appeared to be the most accurate prediction method for this sample (affected limbs: bias 0.3 kg, 95% limits of agreement (LOA) -5.8 to 6.4 kg, typical error as a coefficient of variation (COV) 2.4%, total error of measurement (total error) 2.4%; control limbs: bias -1.3 kg, 95% LOA -9.0 to 6.3 kg, typical error as a COV 2.7%, total error 2.8%).

When the knee OA group performed the knee extension exercise, the Brown, Brzycki, Epley, Lander, Mayhew et al., Poliquin and Wathen prediction methods demonstrated the greatest levels of predictive accuracy. No significant differences in predictive accuracy were found for any of the equations across the affected and control limbs ($p > 0.05$). When an atypical subject was identified and excluded from the analyses, the accuracy of the equations improved further. Typical errors as COVs and total errors for the more accurate prediction methods ranged from 2.5-2.7% and from 2.4-2.9%, respectively. Overall, the Poliquin table appeared to be the most accurate prediction method for this sample (affected limbs: bias 0.9 kg, 95% LOA -4.5 to 6.3 kg, typical error as a COV 2.5%, total error 2.5%; control limbs: bias -0.1 kg, 95% LOA -6.0 to 5.9 kg, typical error as a COV 2.5%, total error 2.4%).

When the knee injury group performed the leg press, the Adams, Berger, Lombardi and O'Connor equations demonstrated the greatest levels of predictive accuracy. No significant differences in predictive accuracy were found for any of the equations across the affected and control limbs ($p > 0.05$). Typical errors as COVs and total errors for the more accurate equations ranged from 2.8-3.2% and from 2.9-3.3%, respectively. Overall, the Berger (affected limbs: bias -0.4 kg, 95% LOA -7.2 to 6.3 kg, typical error as a COV 3.2%, total error 3.2%; control limbs: bias 0.1 kg, 95% LOA -6.6 to 6.7 kg, typical error as a COV 3.1%, total error 3.0%) and O'Connor equations (affected limbs: bias -0.6 kg, 95% LOA-6.8 to 5.7 kg, typical error as a COV 2.9%, total error 3.0%; control limbs: bias -0.2 kg, 95% LOA -6.9 to 6.4 kg, typical error as a COV 2.9%, total error 2.9%) appeared to be the most accurate prediction methods for this sample.

When the knee OA group performed the leg press, the Adams, Berger, KLW, Lombardi and O'Connor equations demonstrated the greatest levels of predictive accuracy. No significant differences in predictive accuracy were found for any of the equations across the affected and control limbs ($p > 0.05$). The typical errors as COVs and the total error values for the more accurate prediction methods were the highest observed in this study, ranging from 5.8-6.0% and from 5.7-6.2%, respectively. Overall, the Adams, Berger, KLW and O'Connor equations appeared to be the most accurate prediction methods for this sample. However, it is possible that the predicted leg press 1-RM values produced by the knee OA group might not have matched actual 1-RM values closely enough to be clinically acceptable for some purposes.

Conclusion: The findings of the current study suggested that the Poliquin table produced the most accurate estimates of knee extension 1-RM performance for both the knee injury and knee OA groups. In contrast, the Berger and O'Connor equations produced the most accurate estimates of leg press 1-RM performance for the knee injury group, while the Adams, Berger, KLW and O'Connor equations produced the most accurate results for the knee OA group. However, the higher error values observed for the knee OA group suggested that predicted leg press 1-RM performance might not be accurate enough for some clinical purposes. Finally, it can be concluded that no single prediction equation was able to accurately estimate both knee extension and leg press 1-RM performance in subjects with knee injuries and knee OA.

1. CHAPTER 1: INTRODUCTION

1.1. STATEMENT OF THE PROBLEM

This study investigated the accuracy of eleven prediction equations and one prediction table when estimating isoinertial knee extension and leg press one repetition maximum performance in subjects with knee injuries and knee osteoarthritis.

As the largest joint in the human body, the knee forms a critical link in the lower limb kinetic chain. However, the knee joint is considered to be relatively weak mechanically because it derives its strength and stability from the ligaments and muscles that surround it, rather than from its bony configuration (Moore, 1992). In addition, the structures of the knee joint must frequently withstand the immense forces that can be generated by the long lever arms of the femur and tibia. Therefore, the articular cartilage, menisci and ligaments of the knee joint are recognized as being particularly susceptible to injuries and degenerative changes (Moore, 1992).

Traumatic injuries and osteoarthritis (OA) have been identified as common musculoskeletal pathologies that can disrupt normal function in the knee joint and consequently lead to significant, ongoing problems in some individuals. With respect to knee injuries, a number of population-based studies have reported incidence rates for acute knee injuries ranging from 3 per 1000 population in the USA (Yawn et al., 2000), to 11 per 1000 population in Finland (Kannus & Järvinen, 1989) to 13 per 1000 population in Denmark (Nielsen & Yde, 1991). In New Zealand, Accident Compensation Corporation (ACC) statistics for 2005 showed that the knee was the most frequently injured site in numerous sports including cricket, golf, field hockey, soccer, tennis and rugby (union, league and touch) (Accident Compensation Corporation, 2005). In addition, the knee was found to be the most frequently injured site overall at cost of NZ$20,773,000 for new claims. Importantly, knee injuries also represented the greatest number of ongoing ACC claims at a cost of NZ$9,424,000.

In a recent effort to identify which specific knee structures were most commonly injured during sporting activities, Majewski, Susanne, & Klaus (2006) investigated

6434 subjects with 7769 sport related knee injuries and found that internal knee injuries accounted for 3482 of the cases (44.8%). Among these internal knee injuries, 45.4% were anterior cruciate ligament injuries, 24% were medial meniscus injuries, 17.6% were medial collateral ligament injuries, 8.2% were lateral meniscus injuries, 2.5% were lateral collateral ligament injuries and 1.5% were posterior cruciate ligament injuries.

With respect to OA, numerous studies have suggested that it is the most common form of arthritis and is a pervasive musculoskeletal pathology worldwide (Arden & Nevitt, 2006; Felson et al., 2000; Woolf & Pfleger, 2003). In New Zealand, a report commissioned by Arthritis New Zealand estimated that approximately 267,300 people, or 8.3% of the population over 15 years of age, were living with OA in 2005. These figures were projected to rise to 381,400 people, or 10.2% of the population, by 2020 (Access Economics Pty Limited, 2005). Although osteoarthritic changes occur in many joints, the knee is one of the most commonly affected (Hurley, Scott, Rees, & Newham, 1997; Sharma, Kapoor, & Issa, 2006). In addition, the prevalence of knee OA has been shown to increase sharply with age. For example, using data from the National Health and Nutrition Examination Study, Davis, Ettinger, Neuhaus & Mallon (1991) reported that the prevalence of knee OA was 10-20% among subjects aged 65-74 and increased to > 30% in those aged 75 and older. However, despite the increased prevalence of knee OA in older adults, it should be recognized that younger adults are not impervious to this condition. For example, it has been suggested that approximately 3.5% to 5% of people between 35 and 54 years of age may experience OA as a consequence of previous knee injuries (Roos, 2005; von Porat, Roos, & Roos, 2004).

While many deleterious outcomes have been identified following knee injuries and the onset of knee OA, it appears that one of the most consistent features associated with these disorders is the development of quadriceps femoris muscle weakness. For example, Tsepis, Vagenas, Ristanis, & Georgoulis (2006) reported that 36 subjects who had sustained ACL injuries 4, 12 and 56 months previously exhibited injured limb quadriceps peak torque deficits of 32%, 30.5% and 21.8%, respectively, when compared to a matched control group. The authors also reported that the 4, 12 and 56 month groups exhibited side-to-side strength deficits of 23.5%, 15.9%, and 10%, respectively, compared to a 2.7% strength asymmetry in the control group. In addition, Pap, Machner and Awiszus (2004) recently investigated maximal quadriceps strength in 68 subjects with mild knee OA, 154 subjects with severe knee OA and 85 control subjects. The authors found that the mild and severe OA groups exhibited strength deficits of 40% and 45%, respectively, when compared to the control group.

Findings such as those described above are important because effective quadriceps contractions are essential if the knee joint is to function optimally. Conversely, quadriceps weakness could potentially moderate an individual's prospects of returning to their previous level of physical activity and might even be a risk factor for further acute injuries and/or ongoing degenerative changes in the knee joint (Myklebust & Bahr, 2005). For example, a number of studies have reported that many individuals are unable to return to their previous level of sporting activity following significant knee injuries (Lohmander, Östenberg, Englund, & Roos, 2004; Myklebust, Holm, Maehlum, Engebretsen, & Bahr, 2003; Roos, Ornell, Gardsell, Lohmander, & Lindstrand, 1995). In addition, it has been demonstrated that knee OA is one of the most common causes of disability in community dwelling older adults, leading to difficulties with activities such as stair climbing, walking, housekeeping and carrying objects (Guccione & Felson, 1994). Consequently, it would seem essential to accurately measure maximal quadriceps strength when performing a physical evaluation of individuals with knee injuries and knee OA.

While numerous strength testing options are available to health professionals, it has been suggested that the technique chosen should be specific to the type of strength training that will be used in the ensuing rehabilitation programme (Brown & Weir, 2001). Importantly, isoinertial weight training is commonly used to increase maximal muscle strength in individuals with knee injuries and knee OA. The gold standard method for measuring maximal isoinertial strength is the one repetition maximum (1-RM) test (Brown & Weir, 2001). However, while 1-RM testing is frequently used in healthy athletic populations, a number of authors have argued that it is time consuming and may be inappropriate for injured populations, since the maximal loading of damaged tissue could potentially increase the risk of re-injury (Grimsby, 2001; Kravitz, Akalan, Nowicki, & Kinzey, 2003). Therefore, several generic prediction equations and tables have been developed to allow the estimation of 1-RM performance from the number of repetitions performed with sub-maximal loads. Importantly, previous studies have demonstrated that 1-RM prediction methods can produce acceptable levels of accuracy in individuals with plantarflexor unit injuries and in healthy populations (Lovelace, 2005; Mayhew, Ball, Arnold, & Bowen, 1992; Mayhew, Kerksick, Lentz, Ware, & Mayhew, 2004). However, despite the reported use of 1-RM prediction equations with injured populations (Grimsby, 2001), the accuracy of these techniques has yet to be investigated in individuals with joint pathologies. If any of these prediction methods were found to be accurate in subjects with knee injuries or knee OA, they might provide health professionals with a more efficient, and perhaps safer, alternative to 1-RM testing in these populations.

1.2. PURPOSE OF THE STUDY

The purpose of this study was to investigate the accuracy of eleven prediction equations and one prediction table when estimating isoinertial knee extension and leg press 1-RM performance in subjects with knee injuries (ligament and/or meniscal) and knee osteoarthritis. Therefore, a descriptive quantitative research study was conducted utilizing a cross-sectional design. The variables of interest were:

1. Each subject's unilateral 1-RMs for the knee extension and leg press exercises.
2. The number of unilateral repetitions to failure (RTFs) that each subject could perform for each exercise using sub-maximal loads. These variables were then entered into eleven 1-RM prediction equations and the Poliquin chart in order to calculate the predicted unilateral 1-RMs for each subject.

The following statistics were then used to assess the level of agreement between the predicted 1-RM values and actual 1-RM values for the knee extension and leg press exercises:

1. In order to ascertain whether there were any significant differences in the predictive accuracy of each equation across the control and affected limbs, paired t-tests were conducted using the percentage difference scores ((predicted 1-RM - actual 1-RM) / actual 1-RM) from the affected and control limbs.
2. Paired t-tests were also performed to determine whether actual 1-RM values were significantly different across the control and affected limbs.

3. Intraclass correlation coefficients between the actual and predicted 1-RM data were calculated to gain an appreciation of "relative reliability".
4. Bland and Altman graphs and level of agreement calculations were used to gain an appreciation of the distribution of error between the actual and predicted 1-RM data.
5. Typical error, typical error as a coefficient of variation and the total error of measurement were calculated to gain an appreciation of the degree of error across the actual and predicted 1-RM values.
6. Finally, the number of subjects with predicted 1-RM values within 5% or less of their actual 1-RM values was determined for each equation.

1.3. SIGNIFICANCE OF THE PROBLEM

Quadriceps muscle weakness is common in individuals with knee injuries and knee OA and may contribute to disability and diminished activity levels. Quadriceps weakness may also increase the risk for further degenerative changes and/or injuries to the knee joint. Therefore, the need for an accurate, safe and efficient method of measuring maximal muscle strength becomes obvious for the identification and quantification of quadriceps deficits in these populations. Such a technique might also assist in the prescription of appropriate strength rehabilitation programmes and consequently facilitate improved levels of functional activity.

2. CHAPTER 2: LITERATURE REVIEW

2.1. INTRODUCTION

This chapter is divided into six main sections. The following section outlines the search strategy used for the literature review. The second section describes the deficits in quadriceps strength that can occur following knee injuries and the onset of knee OA and reviews the mechanisms that may contribute to these deficits. The third section discusses resistance training and the importance of maximal strength testing. The fourth section summarizes the techniques available for assessing maximal muscle strength, including 1-RM strength testing. The fifth section discusses 1-RM prediction equations with an emphasis on the variables that may influence the accuracy of these equations. The chapter concludes with a summary.

2.2. LITERATURE SEARCH

2.2.1. Introduction

The principal reasons for performing the literature search were two-fold. The first goal was to identify studies relating to 1-RM prediction equations and other measures of maximal muscle strength including their accuracy and other associated features. The second objective was to identify articles pertaining to knee injuries and knee OA with a particular emphasis on quadriceps dysfunction.

2.2.2. Search Strategy

2.2.2.1. Inclusion and Exclusion Criteria

Studies were analysed in the literature review if they met the following criteria:

- Human studies examining quadriceps strength following knee injuries and the onset of OA

- Human or animal studies examining the mechanisms that might contribute to quadriceps deficits
- Studies examining resistance training with respect to loading strategies and the importance of maximal strength testing
- Studies examining the techniques used for measuring maximal muscle strength
- Studies examining 1-RM prediction equations or tables as measures of maximal muscle strength
- Studies using subjects who had undergone total knee arthroplasty were excluded
- Case studies were excluded due to their inherent limitations.

2.2.2.2. Search Strategy & Databases/Resources Used

The search strategy was designed to identify articles published in both print and electronic mediums, as well as unpublished studies. The search was limited to English language papers. The following electronic databases and resources were utilized:

- Allied and Complementary Medicine (AMED, 1985+)
- Auckland University of Technology Library Catalogue including E-Journals
- Cochrane Library
- Cumulative Index to Nursing & Allied Health Literature (CINAHL, 1982+)
- Google
- Google Scholar
- ISI Web of Knowledge: Current Contents Connect (1997+)
- EBSCO Health Databases
- Medline via PubMed
- PEDro (Physiotherapy Evidence Database)
- Sports Discus

In addition, the reference lists of articles and texts were manually searched to identify relevant papers and key authors.

2.2.2.3. Search Terms

Each database was searched to identify studies in the following categories:

- Knee injuries and knee OA:
    - Epidemiology
    - Quadriceps deficits
- Mechanisms contributing to quadriceps deficits
- Resistance training with respect to maximal strength testing and loading strategies
- Methods of assessing maximal muscle strength
- 1-RM prediction equations

Search terms were modified as required for each database. Search terms were used individually and were also combined as phrases or using Boolean operators to target studies in each category. The search terms were used in default fields and in specific fields such as abstract, journal and title as required. The names of key authors were also used in the author field. The main search terms used are shown in Table 2.1.

Table 2.1: Terms Used in Literature Search

Search Terms			
Knee	Quadriceps	Resistance	Accura*
Osteoarthritis	Muscle	One	Return*
Anterior	Strength*	Repetition	Resum*
Posterior	Weakness	Rep	Sport*
Cruciate	Deficit	Maximum	Function*
ACL	Assess*	Max	Activity
PCL	Measur*	1RM	Outcome
Medial	Test*	1-RM	Tool*
Lateral	Evaluat*	Prediction	Epidemiology
Collateral	Weight	Equation	History
Ligament	Training	Reliab*	Incidence
Menisc*	Exercise	Valid*	Prevalence

2.3. *KNEE INJURIES & KNEE OA*

2.3.1. Quadriceps Deficits

Numerous adverse outcomes have been identified and investigated following knee injuries and the onset of knee OA. One of the most consistent problems associated with these disorders is the development of quadriceps femoris muscle weakness. Importantly, quadriceps weakness could reduce an individual's prospects of returning to their previous level of physical activity and might even be a risk factor for further acute injuries and/or ongoing degenerative changes in the knee joint. Therefore, a number of issues relating to quadriceps weakness will be discussed in the subsequent sections. The first section describes the magnitude of quadriceps strength deficits following various knee injuries. The second section describes the magnitude of quadriceps strength deficits in populations with knee OA and also presents discussions regarding the possible role of quadriceps weakness in the onset and progression of knee OA. The third section examines the mechanisms that might contribute to quadriceps muscle weakness following a knee injury or the onset of knee OA including pain, effusion, voluntary activation failure, atrophy and immobilization/disuse. The fourth section discusses the relationship between quadriceps weakness and return to sport in individuals with knee injuries, while the final section discusses the relationship between quadriceps weakness and functional activity levels in individuals with knee OA.

Finally, it should be recognized that a vast number of studies have investigated the topics outlined above. Therefore, it was not possible to include all of the available literature in this section of the review. Instead a number of key studies have been discussed to highlight the relevant factors within each section.

2.3.1.1. Knee Injuries and Quadriceps Deficits

The vast majority of studies that have investigated quadriceps strength deficits following knee injuries have focused on the ACL and to a lesser extent the PCL and menisci. These studies have generally demonstrated that significant concentric and/or eccentric quadriceps strength deficits can occur following knee injuries and subsequent surgeries. Importantly, these studies have also found that quadriceps deficits can develop rapidly and may persist for months or years, despite supervised rehabilitation and a return to recreational and/or sporting activities. In addition, many studies have demonstrated that quadriceps strength deficits can occur across a wide range of joint angles and angular velocities. Importantly, these findings suggest that quadriceps deficits following knee injuries could reduce physical performance across an array of functional and recreational activities and even prevent a return to some pre-injury activities. Therefore, a number of key studies will be discussed in the following sections in order to gain an appreciation of the characteristics of quadriceps deficits following ACL, PCL and meniscal injuries.

ACL Injuries and Quadriceps Deficits

It has been demonstrated that significant quadriceps deficits can develop and endure following ACL injury. For example, St Clair Gibson, Lambert, Durandt, Scales, & Noakes (2000) measured quadriceps peak torque values in 17 subjects with chronic ACL deficiency (1-15 years) at an angular velocity of 60º per second (/s). The authors reported that all mean peak torque values for eccentric and concentric quadriceps muscle contractions were significantly lower in the ACL deficient limb compared to the intact limb. The greatest impairments were seen during eccentric quadriceps contractions in the ACL deficient knee where the decrements were of such a magnitude that eccentric mean peak torque values were actually lower than the concentric mean peak torque values. This differed from the uninvolved limb where the eccentric mean peak torque values were significantly higher than the concentric mean peak torque values. In addition, eccentric and concentric quadriceps mean peak torque deficits of approximately 38% and 16%, respectively, were observed in the ACL deficient limbs when compared to the intact limbs.

In addition to general strength deficits, some studies have also found alterations in the quadriceps torque curve patterns of subjects with ACL injuries. Importantly, these studies have suggested that quadriceps weakness can manifest across a variety of contraction modes, joint angles and angular velocities and could consequently have a pronounced effect on knee joint function. For example, Ikeda, Kurosawa & Kim (2002) measured torque curve patterns and maximal isokinetic strength in 48 males at a mean interval of 15 months post-unilateral ACL injury. At an angular velocity of 30º/s, the authors found concentric and eccentric mean peak torque deficits of 15% and 21%, respectively, between the injured and uninjured limbs. The authors also reported that 23% of the subjects exhibited a rapid downward pattern in the torque curve slope when performing concentric quadriceps contractions in their injured limbs. This involved a sharp descending curve from peak torque to torque at slight knee flexion. In addition, 65% of the subjects produced a concave curve when performing eccentric quadriceps contractions from full extension to slight flexion in their injured limbs. In contrast, convex curves were typically produced in normal knees. Importantly, the authors reported that the rapid downward slope pattern and the concave pattern were both seen when the knees were in slight flexion. In turn, the authors argued that this finding might be significant because slight flexion is a position in which anterior displacement of the tibia is known to occur during concentric contractions and in which symptoms of giving way can occur during weight-bearing eccentric contractions.

In a more recent study, Tsepis, Giakas, Vagenas, & Georgoulis (2004) used isokinetic torque curve patterns produced at 60º/s to compare the smoothness of flexion-extension torque production between the intact and ACL deficient knees of 30 male soccer players. The authors reported that many of the subjects (70-83% depending on the level of the signal power) produced isokinetic torque-time curve patterns with higher oscillatory profiles when using their ACL deficient knees. The authors suggested that these higher oscillatory profiles represented abnormal patterns during isokinetic knee extension and reflected more unstable mechanical output from the injured knees. In turn, the authors speculated that this kind of fluctuation in mechanical output may play a role in the functional knee instability that plagues so many individuals with ACL injuries.

A large number of studies have also reported significant quadriceps muscle strength deficits following reconstructive surgery for ACL injuries. In a prospective study, Holm, Risberg, Aune, Tjomsland, & Steen (2000) investigated isokinetic muscle performance over a two year follow-up period in 151 subjects who underwent ACL reconstruction and performed a standardized rehabilitation programme. Using the isokinetic parameter of total work at an angular velocity of 60º/s, the authors reported average quadriceps deficits in the operated limbs of 33% at six months, 17.9% at 12 months and 10% at 24 months. At 240º/s, the authors reported deficits of 24.3% at six months, 17% at 12 months and 10.6% at 24 months. Based on these results, it appears that quadriceps strength deficits can persist for extended periods of time following ACL reconstruction, despite rehabilitation and a return to sporting activities.

In a similar study, Kobayashi, Higuchi, Terauchi, Kobayashi, Kimura & Takagishi (2004) measured concentric quadriceps isokinetic strength at one, six, 12 and 24 months post-surgery in 36 subjects who underwent ACL reconstruction and performed a standardized rehabilitation programme. The authors compared quadriceps mean peak torque at 60º/s across the reconstructed and unaffected limbs and found deficits of 66.9% at one month, 36.8% at six months, 27.1% at 12 months and 10.9% at 24 months. At an angular velocity of 180º/s the authors found quadriceps deficits in the reconstructed limbs of 30.7% at 6 months, 18.2% at 12 months and 9.4% at 24 months. Interestingly, 13 of the 36 subjects in this study had anterior knee pain on kneeling. When the authors compared this subgroup with the other subjects they found the pain group had greater quadriceps deficits at the 60º/s velocity at all follow-up dates, although the differences only reached statistical significance at 12 and 24 months. Based on these results, the authors suggested that significant deficits in quadriceps strength can occur following ACL reconstruction and that these deficits can persist for long periods of time. In addition, the authors suggested that these deficits might be exacerbated by complications such as anterior knee pain.

In another study, Cardone, Menegassi, & Emygdio (2004) used 67 subjects who underwent ACL reconstruction to measure quadriceps isokinetic strength at two, four and six months postoperatively. The subjects in this study participated in a standardized, accelerated rehabilitation programme for six months following surgery. Concentric quadriceps isokinetic strength was assessed at angular velocities of 60º/s, 180º/s and 240º/s, although the 60º/s velocity was not used at the two month follow-up due to safety concerns. When the authors compared concentric quadriceps strength in the operated knees and the intact knees at two months post-surgery they found deficits of 34% at 180º/s and 28% at 240º/s. At four months these deficits were 33% at 60º/s, 24% at 180º/s and 20% at 240º/s. At six months these deficits were 25% at

60º/s, 17% at 180º/s and 12% at 240º/s. While these results appear to be superior to the six month results reported by Kobayashi et al (2004), they still demonstrated that considerable isokinetic quadriceps deficits persisted at slower angular velocities for at least six months.

In a study that utilized isoinertial weight equipment, Augustsson, Thomee, & Karlsson (2004) measured knee extension 1-RM performance in 19 male subjects at an average of 11 (± 2) months post ACL reconstruction. All subjects were at least recreational athletes and 13 (69%) had returned to their previous level of sports participation. In addition, all subjects had received at least six months of physiotherapy post-operatively. The authors reported mean 1-RM values of 53 kg (± 8 kg) for the ACL reconstructed limbs and 62 kg (± 11 kg) for the uninjured limbs, which represented a 14% strength deficit. In addition, the authors reported that 12 subjects (63%) exhibited 1-RM strength values below 90% of the uninvolved limbs. Based on these findings, the authors argued that while some subjects had returned to sport at 11 months post surgery, a number of them had done so with quadriceps strength deficits.

Finally, in a more recent study de Jong, van Caspel, van Haeff, & Saris (2007) measured isokinetic quadriceps peak torque at 60º/s and 180º/s in 191 military personnel who underwent ACL reconstruction (162 males, 29 females; mean age 29 ± 7 years). All subjects performed a standardized rehabilitation programme and the mean interval from injury to reconstruction was 2.2 (± 2.3) years. The authors reported pre-operative side-to-side quadriceps deficits of 17% at 60º/s and 12% at 180º/s in the injured limbs. At 6 months post-surgery, the deficits had increased to 36% at 60º/s and 25% at 180º/s. At 9 months post-operatively, these deficits had reduced to 25% and 18%, respectively and, at 12 months post-operatively, these deficits had decreased further to 19% and 16%, respectively. However, it should be recognized that a considerable number of subjects were lost to follow-up at 9 and 12 months post-surgery because they had recovered sufficiently to return to military duty. Nevertheless, based on their findings, the authors suggested that significant quadriceps strength deficits can persist for long periods of time following ACL reconstruction, despite an intensive military rehabilitation programme.

From the results of the studies described above and many other investigations (see Table 2.2), it is evident that significant quadriceps muscle weakness can occur following ACL injury and reconstructive surgery. In addition, it appears that these deficits can persist for long periods of time despite structured rehabilitation and/or the resumption of sporting activities. Importantly, it has also been demonstrated that quadriceps deficits following ACL injuries can manifest across a variety of contraction modes, joint angles and angular velocities. As a consequence, it seems likely that these deficits could have a profound effect on knee joint function. Therefore, the importance of an efficient, safe and accurate method of measuring quadriceps muscle strength following ACL injuries becomes apparent.

PCL Injuries and Quadriceps Deficits

Far fewer studies have investigated quadriceps weakness following PCL injuries and the evidence for significant differences in strength between PCL deficient and normal knees is less consistent. However, because quadriceps strength may be particularly important for maintaining anterior-posterior knee stability in PCL deficient knees, even small quadriceps deficits could have an impact on knee joint function.

Some studies have demonstrated quadriceps deficits following PCL injury. For example, Shelbourne, Davis, & Patel (1999) measured isokinetic quadriceps strength in 68 subjects with unilateral, chronic (2.3 to 11.4 years), isolated PCL injuries. The authors reported that average quadriceps strength in the PCL deficient limbs was at least 94% of the strength in the uninvolved limbs, with a range of 72% to 123%. In addition, the authors found a statistically significant correlation ($r = 0.59$; $p \leq 0.01$) between total scores on a modified Noyes questionnaire and isokinetic quadriceps muscle strength. The authors reported that patients who subjectively scored their knee at less than 75 points had a mean quadriceps muscle strength of 91% compared with the opposite leg, while patients who subjectively scored 90 points or higher had a mean quadriceps muscle strength of 103% compared with the opposite leg. However, the authors were quick to point out that, in their experience, quadriceps muscle weakness is often the result of a dysfunctional knee, not the cause of the dysfunction. Nevertheless, it should be recognized that some subjects in this athletically active

Table 2.2: Quadriceps Deficits Following ACL Injury and/or Reconstruction

Study	Status	Sample Size	Gender	Mean Age	Rehabilitation and Activity Levels	Mean follow-up period	Strength Assessment Methods	Quadriceps Deficits Compared to Controls	Side-to-Side Quadriceps Deficits
Arangio, Chen, Kalady, & Reed (1997)	ACL-R	N = 33	24 males 9 females	32.3 years	Standardized 5 stage rehabilitation programme post-surgery Activity levels not stated	48.7 ± 6.91 months	Isokinetic: 90º/sec 150º/sec 240º/sec		 12.9% 8.3% 8.5%
Benjuya, Plotqin, & Melzer (2000)	ACL-D Controls	N = 27 N = 27	All males All males	31 years 29 years	Physiotherapy for 3 months following arthroscopic diagnosis of partial ACL tear Activity levels not stated	9 months	Isokinetic: 60º/sec 180º/sec	 32.6% 30.1%	 26.0% 23.4%
Hiemstra, Webber, MacDonald, & Kriellaars (2000)	ACL-R Controls	N = 24 N = 30	16 males 8 females All males	26.2 years 26.3 years	Standardized accelerated rehabilitation post-surgery Activity levels not stated	30 months	Isokinetic: eccentric and concentric at 50, 100, 150, 200, 250º/sec	25% deficit averaged across all velocities and contraction types	
Hole et al.(2000)	ACL-D	N = 10	8 males 2 females	32.8 years	Not stated	Not stated	Isometric: at 40º flexion at 70º flexion		 10% 15%
Järvelä, Kannus, Latvala, & Järvinen (2002)	ACL-R	N= 86	65 males 21 females	30.6 years	Standardized rehabilitation with running at 12-16 weeks and sport permitted after 6 months Activity levels not stated	7.0 ± 0.8 years	Isokinetic: 60º/sec 180º/sec 240º/sec		 10.3% ± 17.7 4.5% ± 13.3 5.2% ± 14.1

Table 2.2 Continued: Quadriceps Deficits Following ACL Injury and/or Reconstruction

Study	Status	Sample Size	Gender	Mean Age	Rehabilitation and Activity Levels	Mean follow-up period	Strength Assessment Methods	Quadriceps Deficits Compared to Controls	Side-to-Side Quadriceps Deficits
Keays, Bullock-Saxton, & Keays, (2000)	Pre & post ACL-R	N = 31	22 males 9 females	27 years	Pre-surgery rehabilitation involving 2 physio sessions and a 6-8 week home programme Activity levels not stated	1 week pre-surgery (mean time from initial injury = 37.7 months)	Isokinetic: 60º/sec 180º/sec		 12% 9%
					Post-surgery rehabilitation involving 9-12 physiotherapy sessions and an ongoing home programme	6 months post-surgery	Isokinetic: 60º/sec 180º/sec		 28.6% 22.6%
Keays, Bullock-Saxton, Newcombe, & Keays (2003)	Pre & post ACL-R	N = 31	22 males 9 females	27 years	Pre-surgery rehabilitation 4-6 weeks. Activity levels not stated	1 week pre-surgery (mean time from initial injury = 33 months)	Isokinetic: 60º/sec 120º/sec		 7.3% 7.8%
					Post-surgery rehabilitation involving 10 physiotherapy sessions over 6 months	6 months post-surgery	Isokinetic: 60º/sec 120º/sec		 12% 10.3%
Kvist, Karlberg, Gerdle, & Gillquist (2001)	ACL-D	N = 12	8 males 4 females	29 years	Rehabilitation not stated. 2 subjects at pre-injury level of competitive sport. Average Tegner score 5.6/10 (range 3-9).	19 ± 3 months	Isokinetic: concentric 60º/sec eccentric 60º/sec (standardized to BMI)	23.3% 28.6%	15.7% 3.4%
	Controls	N = 11	5 males 6 females	27 years					

Table 2.2 Continued: Quadriceps Deficits Following ACL Injury and/or Reconstruction

Study	Status	Sample Size	Gender	Mean Age	Rehabilitation and Activity Levels	Mean follow-up period	Strength Assessment Methods	Quadriceps Deficits Compared to Controls	Side-to-Side Quadriceps Deficits
Lewek, Rudolph, Axe, & Snyder-Mackler (2002)	ACL-D	N = 10	6 males 4 females	28.1 years	Not stated	< 6 months post-injury	Isometric: at 90º knee flex		24.7%
	ACL-R (strong)	N = 8	5 males 3 females	21.4 years		14.3 weeks post-surgery	Isometric: at 90º knee flex		4.7%
	ACL-R (weak)	N = 10	4 males 6 females	25.0 years		20.8 weeks post-surgery	Isometric: at 90º knee flex		32.4%
Mattacola et al (2002)	ACL-R	N = 20	11 males 9 females	25.8 years	All subjects completed rehabilitation programmes (non-standardized, average length 8-10 weeks) Activity levels not stated	18 ± 10 months	Isokinetic: concentric 120º/sec 240º/sec eccentric 120º/sec 240º/sec	 14.5% 12.8% 11.6% 12.4%	 15.4% 9% 6.4% 7.1%
	Controls	N = 20	11 males 9 females	24.5 years					
Pincivero, Heller, & Hou (2002)	ACL-D	N = 7	4 males 3 females	26.7 years	Rehabilitation not stated All subjects involved in regular activity 2-3 times a week (jogging, cycling, aerobics)	49.9 months	Isokinetic: 1.05 rad/sec 3.14 rad/sec	 10.1% 8.7%	
	ACL-R	N = 6	2 males 4 females	22.0 years		49.7 months	1.05 rad/sec 3.14 rad/sec	10.1% 6.5%	
	Controls	N = 10	5 males 5 females	24.1 years			(standardized to body mass)		

Table 2.2 Continued: Quadriceps Deficits Following ACL Injury and/or Reconstruction

Study	Status	Sample Size	Gender	Mean Age	Rehabilitation and Activity Levels	Mean follow-up period	Strength Assessment Methods	Quadriceps Deficits Compared to Controls	Side-to-Side Quadriceps Deficits
Strauss et al (1998)	ACL-R	N = 15	Not stated	Not stated	Not stated	12 weeks	Isokinetic TRAT:		
							concentric at 60, 120 and 180º/sec		25.4%
							eccentric at 60º/sec		30.5
						18 weeks	concentric at 60, 120 and 180º/sec		21.4%
							eccentric at 60º/sec		17.6%
Wojtys & Huston (2000)	ACL-R	N = 25	16 males 9 females	23.8 years	Identical rehabilitation By 18 months 20 subjects (80%) believed they had regained pre-surgery levels of function		Isokinetic:		
						Pre-surgery	60º/sec		18%
						6 months	60º/sec		24%
						12 months	60º/sec		14%
						18 months	60º/sec		10%
							(standardized to body weight)		

ACL-D = Anterior cruciate ligament deficient, ACL-R = Anterior cruciate ligament reconstructed, BMI = Body mass index, TRAT = Truncated range average torque population (mean age 25.2 years at time of injury) exhibited quadriceps deficits at an average follow-up time of 5.4 years post-injury.

In a more recent study, Chen, Chen, Shih, & Chou (2004) examined isokinetic knee extensor peak torque in 29 subjects who underwent PCL reconstruction. Although the data were not described in detail (angular velocity and type of contraction were not reported), the results appeared to demonstrate a mean pre-operative quadriceps strength deficit of 27.1% in the involved limbs when compared to the uninvolved limbs. At a minimum of three years post-surgery, this deficit had decreased to 13.2%. In addition, the authors reported that, preoperatively, three subjects had extensor strength ratios > 90% (peak muscle torque of the involved side/peak muscle torque of the uninvolved side x 100%), five subjects had ratios of 80%-90% and 21 subjects had ratios < 80%. At follow-up, 13 subjects had ratios > 90%, 11 subjects had ratios of 80%-90% and five subjects had ratios < 80%. Although these results showed a significant improvement in quadriceps strength at a minimum of three years post-surgery, they also demonstrated that many subjects had considerable quadriceps deficits following PCL injury. In addition, these deficits apparently continued for a number of years post-surgery, despite participation in a rehabilitation programme.

In contrast, other studies have failed to demonstrate significant differences in quadriceps strength between the injured and uninjured limbs of individuals with PCL injuries. For example, Keller, Shelbourne, McCarroll, & Rettig (1993) evaluated isokinetic knee extensor strength in 40 subjects with isolated PCL injuries (average time from injury 6 years) and reported that mean isokinetic quadriceps strength scores for the injured limbs reached 99% of those found in the uninvolved limb. However, the results of the isokinetic testing were not described in detail. For example, testing was performed at angular velocities of 60º/s, 180º/s and 240º/s but the mean scores for these different velocities were not provided. Therefore, it is impossible to ascertain whether larger deficits may have been present at certain speeds but not at others.

A more recent study also failed to demonstrate significant differences in quadriceps strength between uninjured and PCL deficient limbs. Inoue, Yasuda, Yamanaka, Wada, & Kaneda (1998) measured concentric quadriceps isokinetic peak torque in 12 subjects with unilateral, chronic (1-16 years) PCL injuries and found statistically non-significant ($p < 0.05$) quadriceps deficits in the involved limbs of 4.2% and 2.6% at angular velocities of 30º/s and 60º/s, respectively. However, it should be noted that the measurements were taken at an average of four years post-injury and it was not reported whether the subjects participated in a rehabilitation programme.

Despite the findings of the two studies described above, an investigation by MacLean, Taunton, Clement, & Regan (1999) provided a caveat. These authors measured concentric and eccentric mean average and average peak isokinetic knee extension torque in 17 subjects with unilateral, isolated PCL injuries sustained at least six months previously. As with Keller et al. (1993) and Inoue et al. (1998), the authors reported that no significant differences in concentric or eccentric quadriceps strength were found between the injured and uninjured limbs. However, the authors also calculated the ratios of eccentric to concentric average peak isokinetic torque in the injured and uninjured limbs and reported values of 1.08 and 1.07, respectively. The authors found these values represented considerable bilateral, eccentric quadriceps strength deficits when compared to the strength ratios reported previously for healthy subjects by Shirakura, Kato, & Udagawa (1992) and Griffin, Tooms, vander Zwaag, Bertorini, & O'Toole (1993). Based on these findings, MacLean et al. (1999) suggested that eccentric quadriceps strengthening should be incorporated into rehabilitation programmes designed to manage chronic, isolated PCL injuries.

In conclusion, it appears that the results of studies investigating quadriceps deficits following PCL injury or PCL reconstructive surgery are inconsistent. However, it could be argued that sufficient evidence exists to suggest that quadriceps weakness can occur regularly in PCL deficient populations. In addition, it should be acknowledged that quadriceps strength may be particularly important in PCL deficient knees because a strong extensor mechanism might help to maintain anterior-posterior knee stability and might also help to compensate for additional stresses placed on the patellofemoral joint (MacLean et al., 1999). Therefore, the importance of an efficient, safe and accurate method of measuring quadriceps muscle strength following PCL injuries becomes apparent.

Meniscal Injuries and Quadriceps Deficits

Several studies have described quadriceps strength deficits following meniscal injuries and arthroscopic meniscectomy. These deficits have been found across a range of time frames, joint velocities and injury types which suggests that they could have a significant impact on knee joint function. For example, Matthews & St Pierre (1996) investigated peak isokinetic knee extensor torque at two week intervals for three months in 22 subjects (35.1±9.2 years of age) who underwent arthroscopic partial meniscectomy. Although the primary purpose of the study was to examine the spontaneous recovery of muscle strength following meniscectomy, it should be noted that all subjects were instructed in a home exercise program in order to meet ethical requirements (no resistance exercises were performed). Prior to partial meniscectomy, the authors reported that the involved quadriceps were weaker than the uninvolved quadriceps at all angular velocities tested (60º/s, 120º/s, 180º/s and 240º/s). However, the deficits only reached statistical significance ($p < 0.01$) at 60°/sec (15% deficit). At two weeks post-surgery, these deficits had increased to 40% at 60º/s, 30% at 120º/s, 29% at 180º and 25% at 240º/s. At four and six weeks post-surgery, the quadriceps deficits had decreased considerably, although the side-to-side differences at six weeks still reached statistical significance at 60º/s (20% deficit), 120º/s (17% deficit) and 180º/s (17% deficit). The improvements in quadriceps strength slowed after six weeks and at 12 weeks the results demonstrated ongoing deficits of 14% at 60º/s, 12% at 120º/s, 11% at 180º/s and 9% at 240º/s. Based on these results, the authors suggested that quadriceps strength decreased significantly post-meniscectomy but spontaneously returned to pre-surgery levels after four to six weeks. However, the authors also argued that since quadriceps deficits persisted at 12 weeks post-surgery, a specific strength training programme might be required post-meniscectomy to return quadriceps strength to the same level as the uninvolved limb.

In a study utilizing isokinetic knee extension work, Moffet, Richards, Malouin, Bravo, & Paradis (1998) examined the relationship between the type of meniscal lesion (bucket-handle, flap or degenerative tears) and work deficits in 35 male subjects. When the authors compared the injured limbs and uninjured limbs they found isokinetic extension work deficits of 36% in the bucket-handle tear group ($n = 12$), 22% in the flap tear group ($n = 15$) and 17% in the degenerative tear group ($n = 8$) at an angular velocity 30º/s. At an angular velocity of 180º/s, the authors reported deficits of 38% for the bucket-handle group, 14% for the flap group and 12% for the degenerative group. When the three types of meniscal tears were combined into one group, isokinetic knee extension work deficits of 26% and 22% were found at

30º/s and 180º/s, respectively. Based on these findings, the authors suggested that significant quadriceps weakness can occur in individuals with meniscal lesions and that that the magnitude of the deficits may be influenced by the type of lesion.

In a more recent study, Gapeyeva, Paasuke, Ereline, Pintsaar, & Eller (2000) measured peak isokinetic quadriceps torque at one, three, and six months post-operatively in 21 male subjects (mean age 26.4±1.9 years) who underwent arthroscopic partial medial meniscectomy and performed a standardized rehabilitation programme. When the authors compared isokinetic quadriceps peak torque in the involved and uninvolved limbs at an angular velocity of 60º/s they found deficits of 28.6% at one month, 19.8% at three months and 18.2% at six months. At 180º/s, the authors observed deficits of 31% at one month, 15.8%, at three months and 9.2% at six months, although the difference at six months did not reach statistical significance ($p > 0.05$). Based on these results, it could be argued that significant isokinetic quadriceps muscle weakness can occur following arthroscopic meniscectomy and that these deficits can persist at slower isokinetic speeds for at least six months post-surgery, despite participation in a rehabilitation program.

From the results of the studies described above it is evident that significant quadriceps muscle weakness can occur following meniscal injuries and subsequent surgery. In addition, it appears that these deficits can persist for long periods of time despite participation in structured rehabilitation programmes. Importantly, it has also been demonstrated that quadriceps deficits following meniscal injuries can manifest across a variety of injury types and angular velocities. As a consequence, it seems likely that these deficits could have a significant impact on knee joint function. Therefore, the importance of an efficient, safe and accurate method of measuring quadriceps muscle strength following meniscal injuries becomes apparent.

Summary

Based on the studies reviewed in this section it is evident that significant and enduring quadriceps muscle weakness can occur following injury and/or surgery involving the ligaments and menisci of the knee. In addition, these deficits have been found across a variety of joint angles, angular velocities and contraction modes which suggests that they might have a wide ranging impact on knee joint function. Thus, it would appear vital that clinicians have an accurate and safe means of assessing quadriceps muscle strength when working with these patient populations.

2.3.1.2. Knee Osteoarthritis

Studies have demonstrated that quadriceps weakness and voluntary activation deficits are common occurrences in individuals with knee OA (Hurley et al., 1997). As with knee injuries, it has been found that these deficits can occur across a wide range of contraction modes, joint angles and angular velocities. Importantly, these findings suggest that quadriceps deficits associated with knee OA could reduce physical performance across an array of functional and recreational activities and potentially lead to disability. In addition, it has also been suggested that quadriceps weakness might play a role in the onset of knee OA and/or contribute to its progression. Therefore, all of these issues will be discussed further in the following sections.

Knee OA and Quadriceps Deficits

A number of studies have demonstrated significant quadriceps strength deficits and voluntary activation deficits in subjects with knee OA. For example, Hurley, Scott, Rees, & Newham (1997) measured maximal isometric quadriceps force and voluntary activation in 103 knee OA subjects and 25 matched control subjects. The authors reported that the knee OA subjects and the control subjects generated mean maximal isometric quadriceps forces of 235 Newtons (N) (95% CI 209-261 N) and 335 N (95% CI 308-361 N), respectively. The difference between the group means was 100 N (95% CI 136-63 N) or 30%. In addition, the subjects with knee OA exhibited 20.5% (95% CI 13-25%) less median voluntary quadriceps activation than the control group. Based on these findings, the authors suggested that the subjects with knee OA had weaker quadriceps muscles than the control subjects and that incomplete voluntary activation may have contributed to this weakness.

Hassan, Mockett, & Doherty (2001) also assessed maximal isometric quadriceps force and voluntary activation in a group of 59 subjects with knee OA and 49 matched control subjects. The authors reported that the knee OA subjects and the control subjects generated mean maximum voluntary contractions of 14.7 kilogram-force (kgf) (95% CI: 12.54-16.86 kgf) and 22.5 kgf (95% CI: 19.9-24.61 kgf), respectively.

The difference between the group means was 7.8 kgf (95% CI: 4.40-10.72 kgf) or 35%. In addition, the knee OA subjects exhibited 21.4% (95% CI: 11.51-31.34%) less voluntary quadriceps activation than the control group. Importantly, the percentage deficits in isometric quadriceps force (35%) and voluntary activation (21.4%) described in this study appear to be similar to those reported for the same variables in the Hurley et al. (1997) study (30% and 20.5%, respectively), despite the methodological differences between the studies.

In a more recent study, Pap, Machner and Awiszus (2004) also found significant quadriceps strength deficits and voluntary activation deficits in subjects with different stages of knee OA. The authors used a twitch interpolation technique to measure quadriceps voluntary activation and maximum voluntary contraction in 68 subjects with Outerbridge stage II (mild) OA, 154 subjects with Outerbridge stage IV (severe) OA and 85 age matched control subjects. The authors reported that quadriceps strength was significantly lower in the subjects with stage II OA (75.9 ± 41.7 Nm, range 15.7–216.1 Nm) and stage IV OA (70.3 ± 36.9 Nm, range 13.0–290.9 Nm), when compared to the control group (126.8 ± 47.3 Nm, range 44.1–279 Nm). These differences represented mean quadriceps deficits of 40% for the stage II OA group and 45% for the stage IV OA group, when compared to the control group. With respect to voluntary activation of the quadriceps muscles, the authors reported that activation values were significantly higher in the control group (89.3% ± 8.0, range 55.4–98%) compared to the stage II OA group (70.8 ± 16.0, range 4.5–97.3%) and the stage IV OA group (77.2± 13.2, range 37.5–97.5%).

Finally, a study by Hortobágyi, Garry, Holbert, & Devita (2004) found significant deficits in isokinetic quadriceps strength, force steadiness and force accuracy in 20 subjects with knee OA when compared to 20 matched controls. With respect to force accuracy (matching 50N and 100N target forces), the knee OA subjects produced 136% more error during eccentric contractions and 107% more error during concentric contractions when compared to the control subjects. The authors reported that these errors resulted from overshooting the targets. With respect to force steadiness, the knee OA subjects displayed significantly less stable quadriceps force production when compared to the control subjects, especially during eccentric contractions. Overall the OA subjects were 155% less steady than controls. With respect to maximal voluntary quadriceps strength, the knee OA subjects produced 63% less total quadriceps force than control subjects, with eccentric deficits of 76% and isometric and concentric deficits of 56%. Based on these findings, the authors suggested that this combination of reduced maximal force production, force steadiness and force accuracy might represent a general impairment in the ability to generate and control maximal and sub-maximal forces, especially during eccentric quadriceps contractions. In turn, it seems likely that such deficits could have a significant impact of knee joint performance across a variety of functional and recreational activities.

In conclusion, it appears that significant quadriceps muscle weakness can occur in individuals with knee OA and that decreased voluntary muscle activation may contribute to this weakness. As a consequence it seems likely that these deficits could have a significant effect on knee joint function. Therefore, the importance of an efficient, safe and accurate method of measuring quadriceps muscle strength in individuals with knee OA becomes apparent.

Quadriceps Deficits and the Development of Knee OA

Presumably based on the premise that stronger muscles can generate protective reflexes and shock absorbing forces to help prevent joint damage (Hurley, 2003; Mikesky, Meyer, & Thompson, 2000), some studies have suggested that quadriceps weakness may be a risk factor for the development of knee OA. For example, Slemenda, Brandt, Heilman, Mazzuca, Braunstein, Katz, & Wolinsky (1997) investigated the association between lower extremity weakness, knee OA and pain in 462 subjects, of which 145 had radiographic evidence of tibiofemoral and/or patellofemoral OA. Consistent with many other studies, the authors reported that isokinetic quadriceps peak torque was lower in the participants with OA than in those without OA. However, the authors also found that among women with isolated tibiofemoral OA this knee extensor weakness was present even in asymptomatic subjects. Importantly, the authors argued that the presence of quadriceps weakness in subjects with asymptomatic knee OA is consistent with the possibility that quadriceps muscle weakness might precede knee OA and therefore might also be a potential primary risk factor for the development of knee OA.

In a second study, Slemenda, Heilman, Brandt, Katz, Mazzuca, Braunstein, & Byrd (1998) used 280 subjects (139 males and 141 females) from the original sample of 462 subjects to prospectively investigate whether baseline quadriceps weakness was a risk factor for incident radiographic knee OA. The authors measured quadriceps isokinetic peak torque at 60º/s and used baseline and follow-up x-rays (mean interval 31.3 months) to establish the onset of knee OA. The authors reported that knee OA was associated with greater body weight in females but not in males. The females who developed knee OA were on average 23% heavier ($p < 0.001$) than those without OA, while those with stable unilateral knee OA were on average 17% heavier ($p < 0.001$). With respect to quadriceps strength, the authors reported that after adjusting for body weight, peak torque was 18% lower at baseline among female subjects who developed OA compared to those who did not ($p = 0.053$). However, for the male subjects, adjusted quadriceps strength was similar in those who developed OA and those who did not. In addition, a strong negative correlation ($r = -0.740$, $p = 0.003$) was found between body weight and quadriceps strength in the 13 females who developed knee OA (i.e. the greater the body weight, the lower the quadriceps strength). In contrast, a modest positive correlation was found between body weight and quadriceps strength for the 14 males who developed knee OA (i.e. the greater the body weight, the greater the quadriceps strength). Based on these findings, the authors suggested that the pathogenesis of knee OA might be different in males and females and that reduced quadriceps strength relative to body weight might be a risk factor for the development of knee OA in women.

A prospective study by Thorstensson, Petersson, Jacobsson, Boegard, & Roos (2004) also appears to support the contention that quadriceps weakness might be a risk factor for knee OA. The authors investigated whether a reduced level of lower extremity functional performance predicted radiographic knee OA using 148 subjects (35-54 years old) with chronic knee pain drawn from a population based cohort. Weight-bearing tibiofemoral radiographs were taken at baseline and 5 years later and were classified as osteoarthritic (Kellgren and Lawrence grade ≥ 1) or non-osteoarthritic (Kellgren and Lawrence grade 0). In addition, a number of predictors were measured. These included age, sex, body mass index, baseline knee pain, and three tests of lower extremity functional performance involving (1) the maximum number of one-leg rises from sitting, (2) a timed 300 m walk, and (3) timed one leg standing balance. The authors reported that the maximum number of one-leg rises performed at baseline predicted the development of knee OA five years later and remained significant even when controlling independently for age, sex, body mass index, and baseline pain. Based on these results, the authors suggested that reduced lower extremity functional performance was an early sign of knee OA and might even be a risk factor for the development of knee OA. However, it should be recognized that the functional test of rising on one leg from sitting is a complex task that challenges multiple muscle groups as well as coordination. Therefore, it could be argued that this task may not be representative of quadriceps strength alone. However, the authors did describe unpublished evidence which suggests that a moderate correlation exists between rising from sitting on one leg and knee extension strength as measured by a hand-held dynamometer (n=47, r=0.64).

Finally, in a more recent study, Ikeda, Tsumura, & Torisu (2005) assessed the association between age-related muscle atrophy and incident radiographic knee OA using 38 asymptomatic female subjects (21 women in their thirties and 17 women in their sixties). The authors reported that quadriceps cross sectional areas were smaller among the women in their sixties compared to those in their thirties, suggesting age related muscle atrophy. In addition, incident radiographic OA (Kellgren and Lawrence grade 2) was observed in six of the 17 women in their sixties and the authors reported that quadriceps-dominant muscle atrophy was even more marked in these subjects compared to those without OA (on average 12% smaller). In turn, the authors argued that age-related quadriceps-dominant muscle atrophy might play a role in the pathogenesis of knee OA, since the women in this study were asymptomatic and had no other history, signs or symptoms of knee problems.

Although the authors of the studies described above have argued that quadriceps weakness might be a risk factor for the development of knee OA, it is also possible that OA preceded and actually led to the observed deficits. For example, it has been suggested that even asymptomatic knee OA could result in abnormal discharge from articular mechanoreceptors and consequently lead to quadriceps muscle inhibition (Baker et al., 2004). However, even if quadriceps weakness is not a risk factor for the development of knee OA, it would not diminish the fact that these two phenomena are often inextricably linked.

In conclusion, the contention that quadriceps weakness might play a role in the aetiology of knee OA appears to be plausible, although the results of studies investigating this issue are equivocal. In any case, the possibility that quadriceps weakness might contribute to the onset of knee OA further emphasizes the need for an efficient, safe and accurate method of measuring quadriceps muscle strength.

Quadriceps Deficits and the Progression of Knee OA

In addition to potentially playing a role in the development of knee OA, it has been suggested that quadriceps weakness might play a role in the progression of knee OA. This contention appears to be based on the premise that muscle weakness may perpetuate a cycle of decreased joint stability, diminished proprioception and consequently joint degradation (Thorstensson et al., 2004). Importantly, the results of some of studies have supported this proposition. For example, Baker, Xu, Zhang, Nevitt, Niu, Aliabadi, Yu, & Felson (2004) investigated the relationships between pain, isometric quadriceps strength and compartment-specific knee OA in 2472 Chinese subjects (> 60 years of age). The authors were unable to detect any significant association between quadriceps weakness and asymptomatic OA in isolated knee compartments. In contrast, they found a strong relationship between quadriceps weakness and asymptomatic combined patellofemoral/tibiofemoral OA. Based on the assumption that asymptomatic, isolated knee OA might represent a milder and/or earlier form of the disease process, the authors suggested that these results support the hypothesis that quadriceps weakness contributes to the progression of knee OA.

In a study described in the previous section, Thorstensson et al. (2004) also explored a number of variables to determine whether they might contribute to the progression of knee OA. While the authors found that none of the variables they measured could predict the progression of existing radiographic knee OA with statistical significance, they did report that the subjects who experienced OA progression tended to perform fewer one-leg rises from sitting, have higher body mass indices and shorter one leg standing times. While not statistically significant, these trends appeared to suggest that diminished lower extremity functional performance, possibly involving quadriceps weakness, might play some role in the progression of knee OA.

While some studies have suggested that quadriceps weakness contributes to the progression of knee OA, others have disputed this contention. For example, Brandt, Heilman, Slemenda, Katz, Mazzuca, Braunstein, & Byrd (1999) used 82 subjects with radiographically diagnosed unilateral or bilateral knee OA to investigate the relationship between quadriceps weakness and the progression of knee OA. At baseline the authors took measures of lower extremity lean tissue mass and quadriceps isokinetic peak torque at 60º/s. At follow-up (mean interval 31.3 months) repeat x-rays were performed to establish the progression of knee OA. Of the original 82 subjects, 14 females and 3 males exhibited radiographic progression of knee OA. Further analysis of the data relating to males with progressive knee OA was not performed because of the low subject numbers. The authors reported that mean quadriceps peak torque before and after adjustment for lower extremity muscle mass was about 9% lower in the females with progressive OA when compared to the females with stable radiographic OA. Interestingly, the authors stated that this difference was not statistically significant (p value not reported) and suggested that factors other than quadriceps weakness might be more important in the progression of knee OA. However, it could also be argued that these findings appear to support a trend which suggests that quadriceps weakness plays at least some role in the progression of knee OA.

Finally, it should be recognized that at least one study has suggested that greater quadriceps strength may actually increase the risk of tibiofemoral OA progression in certain populations. Sharma, Dunlop, Cahue, Song, & Hayes (2003) investigated the relationship between isokinetic quadriceps peak torque, knee laxity, knee alignment and OA progression in 237 subjects over an 18 month period. The authors reported that, in general, greater quadriceps strength did not reduce the likelihood of subsequent OA progression. With respect to baseline alignment the authors found that quadriceps strength had no effect on OA progression in more neutral knees. However, in misaligned knees OA progression was considerably more likely in subjects with higher quadriceps strength versus lower quadriceps strength (50% vs 26.3%). With respect to baseline laxity the authors found that higher versus lower quadriceps strength was associated with increased OA progression in both low laxity (19.2% vs 14.3%) and high laxity (24.4% vs 14.4%) knees. Based on these results, the authors suggested that in the case of lax and/or misaligned OA knees, greater quadriceps strength may actually accelerate the progression of OA. However, while the results of this study suggest that greater quadriceps strength might not always be beneficial for individuals with knee OA, it does not negate the argument that an accurate and safe method of assessing baseline quadriceps strength is required for these populations.

In conclusion, it appears that although the contention that quadriceps weakness might contribute to the progression of knee OA is plausible, the results of studies investigating this issue are currently discordant. Nevertheless, the possibility that quadriceps weakness plays some role in the progression of knee OA reinforces the need for a safe, efficient and accurate method of measuring quadriceps strength.

Summary

A number of studies have demonstrated that, as with knee injuries, knee OA is often associated with significant and enduring quadriceps muscle weakness. It has also been shown that these deficits can occur across a wide range of contraction modes, joint angles and angular velocities. Importantly, these findings suggest that quadriceps deficits associated with knee OA could reduce knee joint performance across an array of functional and recreational activities and consequently lead to disability. In addition, it has been argued that quadriceps weakness might play some role in the onset and/or progression of knee OA. Therefore, these findings further support the argument that an efficient, safe and accurate clinical method of assessing quadriceps strength is required when evaluating individuals with knee OA.

2.3.1.3. The Mechanisms Associated with Quadriceps Deficits

Having established that significant quadriceps strength deficits can occur frequently in individuals with knee injuries and knee OA, there remains the need to discuss some of the mechanisms that may give rise to muscle weakness in these populations. A number of factors that might contribute to quadriceps weakness have been identified including pain, effusion, muscle activation failure, muscle atrophy and immobilization/disuse. Although these mechanisms are discussed individually in the following sections, it should be recognized that they are likely to be inextricably linked in many individuals with knee injuries and knee OA.

Pain

Pain has been shown to have an inhibitory effect on maximum voluntary muscle contraction. This has been demonstrated by Graven-Nielsen, Lund, Arendt-Nielsen, Danneskiold-Samsøe, & Bliddal (2002) who measured maximal isometric quadriceps muscle torque in 8 subjects before, during and after experimentally inducing muscle pain. The authors reported that experimental muscle pain significantly reduced the quadriceps torque produced during voluntary isometric knee extension. However, when electrical stimulation was applied using a twitch interpolation technique, quadriceps torque was produced at levels similar to the control session, despite the muscle pain. Based on these results, the authors argued that experimentally induced pain can reduce torque without compromising the mechanical capability of the muscle, thus implicating a central inhibitory mechanism.

The findings of a more recent investigation also suggested that pain may operate through a central inhibitory mechanism. Farina, Arendt-Nielsen, Merletti, & Graven-Nielsen (2004) examined the effects of muscle pain intensity on motor unit firing rate and conduction velocity by measuring surface and intramuscular EMG activity in the tibialis anterior (TA) muscles of 12 healthy subjects. The subjects performed submaximal isometric contractions of the right TA muscle both before and after pain was experimentally induced using three incremental intramuscular injections of hypertonic saline. In addition, the subjects performed submaximal isometric contractions of the left TA muscle both before and after injection of isotonic (non-painful) saline. The authors reported that the experimentally induced pain resulted in a decreased motor unit firing rate that was correlated to pain intensity. In contrast, the firing rate of the active muscle units did not change significantly under the control conditions (i.e. before injection in both legs and following injection of isotonic saline in the left leg). In addition, the authors reported that single motor unit conduction velocities did not differ significantly between any of the conditions which suggested that injection of the hypertonic saline did not alter the muscle fibre membrane properties in the observed motor units. Based on these results, the authors argued that experimentally induced pain may influence submaximal isometric muscle activity through a central inhibitory motor control mechanism.

In a similar experiment, Farina, Arendt-Nielsen, & Graven-Nielsen (2005) provided further evidence implicating a central inhibitory mechanism in the effect of pain on muscle activity. These authors investigated EMG voluntary activity and M-wave properties during electrically elicited and voluntary contractions of the tibialis anterior muscles in 12 healthy subjects. Measurements were performed in the left leg before and after isotonic saline injections and in the right leg after three incremental injections of hypertonic saline. The authors reported that M-wave conduction velocity, amplitude, and spectral content did not change with the injections of painful hypertonic saline. However, surface EMG amplitude decreased during the voluntary contractions as the levels of nociceptive input increased. The authors argued that the unaltered M-wave properties showed that the reduction in muscle activity was not due to changes in muscle fibre membrane properties or impaired neuromuscular transmission, based on the premise that evoked M-waves are affected only by sarcolemma excitability and intracellular action potentials and thus provide a direct indication of the condition of the peripheral muscular system. Instead, the authors suggested that the stimulation of nociceptive afferents by hypertonic saline injection induces a centrally mediated inhibition of muscle activity.

As well as having an effect on isolated isometric muscle contractions, it has been shown that pain can alter motor control strategies during dynamic exercises. Ervilha, Farina, Arendt-Nielsen, & Graven-Nielsen (2005) measured fibre conduction velocity in the biceps muscles and surface EMG activity in the upper trapezius, biceps, triceps, and brachioradialis muscles of 10 healthy subjects while they performed maximum speed elbow flexion/extension movements. Measurements were performed following injection of (1) hypertonic saline in the biceps, (2) hypertonic saline in both biceps and triceps, and (3) isotonic saline in the biceps muscle. The authors reported that the subjects could perform the exercise with the same mechanical output under all of the conditions, but the presence of pain changed both the relative contribution of the synergistic muscles and the pattern of motor unit activation within the painful muscles. Based on these findings, the authors argued that the muscle activation strategy used to perform and sustain the exercise over time was significantly altered by the presence of pain. Although speculative, it is possible that these findings could be extrapolated to individuals with knee OA or knee injuries. For example, knee pain might lead to diminished quadriceps muscle activity and therefore altered synergistic motor strategies during the performance of physical activities involving the knee.

In conclusion, it is clear from the studies discussed above that pain can have a detrimental effect on voluntary muscle activation, most likely through central inhibitory pathways. Therefore, pain generated by knee injuries or knee OA could potentially contribute to quadriceps strength deficits.

Effusion

Another potential source of presynaptic, ongoing reflex inhibition of the quadriceps muscles is the intra-articular knee joint effusion which often accompanies knee injuries and knee OA. Hopkins, Christopher, Jeffrey, & Thomas (2002) argued that an effusion might increase activity in slowly adapting Ruffini endings in the knee joint capsule, which in turn might stimulate Ib inhibitory interneurons, ultimately leading to a reduction in quadriceps alpha motoneuron output. In addition, Palmieri, Weltman, Edwards, Tom, Saliba, Mistry, & Ingersoll (2005) proposed that supraspinal descending pathways involving GABA-ergic interneurons might also contribute to inhibition of the quadriceps muscles following knee joint effusion.

Importantly, some studies have demonstrated that experimentally induced knee effusion can result in significant quadriceps inhibition. For example, McNair, Marshall, & Maguire (1996) investigated the effects of excessive fluid in the knee joint on quadriceps performance and found that isokinetic quadriceps peak torque decreased by 30% immediately following the injection of fluid into the joint.

In a more recent study, Hopkins (2006) also demonstrated decreases in knee extension peak torque and peak power following experimentally induced knee effusion. The author reported reductions in knee extension peak torque of 28%, 25% and 23% at 0, 30 and 60 minutes post-injection, respectively. In addition, the authors reported reductions in knee extension peak power of 33%, 23% and 29% at 0, 30 and 60 minutes post-injection, respectively.

However, while the studies described above demonstrated that knee joint effusion is associated with ipsilateral quadriceps muscle inhibition, a recent investigation by Palmieri, Ingersoll, Edwards, Hoffman, Stone, Babington, Cordova, & Krause, (2003) failed to find evidence that knee effusion leads to contralateral quadriceps inhibition. In this study Hoffman reflex (H-reflex) and M-wave measurements were collected using surface electromyography from the vastus medialis muscles of 8 subjects who received an injection of 60 ml of saline into the knee joint of their dominant leg. The authors reported that both maximum H-reflex and maximum H-reflex/maximum M-wave ratios were decreased in the ipsilateral vastus medialis muscles at 10, 20 and 30 minutes post effusion. However, no changes were detected on the contralateral side. Based on the premise that a reduction in the H-reflex indicates an inhibitory action from knee joint afferents on the quadriceps' motor-neuron pool, these findings appeared to demonstrate that knee effusions resulted in arthrogenous inhibition of the ipsilateral but not contralateral quadriceps muscles. Therefore, Palmieri et al. (2003) suggested that pain-free knee joint effusions are not responsible for the bilateral quadriceps activation deficits which sometimes occur after unilateral joint injury.

In conclusion, it appears that joint effusions may contribute to the significant ipsilateral quadriceps strength deficits that can occur in subjects with knee injuries and knee OA. However, it seems unlikely that joint effusions can explain the bilateral quadriceps strength deficits that are sometimes observed in these populations.

Voluntary Activation Failure

While factors such as pain and effusion can cause quadriceps weakness in individuals with knee injuries and knee OA, it has also been suggested that incomplete voluntary activation (VA) of the muscle may contribute to strength deficits, not only in the involved limb but also in the uninvolved limb.

With respect to knee injuries, a number of studies have demonstrated large voluntary activation deficits following ACL injuries. For example, Urbach, Nebelung, Weiler, & Awiszus (1999) used a twitch-interpolation technique to measure quadriceps activation failure in 22 male subjects with isolated ACL ruptures and 19 matched controls. The authors reported that the ACL deficient subjects exhibited mean voluntary activation deficits of 16.1% in the involved limbs and 15.3% in the uninvolved limbs. In contrast, the control subjects exhibited mean activation deficits of 8.9%. However, this study had a number of limitations. For example, there was a mixture of acute and chronic ACL deficient subjects included in the sample. In addition, the authors reported that while most of the subjects exhibited a voluntary-activation distribution almost identical to the control group, 23% had voluntary activation deficits of greater than 20% and these individuals were largely responsible for the significant mean deficit. However, in a more recent study Urbach, Nebelung, Becker, & Awiszus (2001) provided further evidence of significant and lasting quadriceps voluntary activation deficits in individuals with ACL injuries. The authors used a twitch interpolation technique to investigate quadriceps voluntary activation in 12 male subjects before and after ACL reconstructive surgery and in 12 matched control subjects. Prior to surgery the authors found that the ACL deficient subjects demonstrated mean voluntary activation deficits of 25.1% on the injured side and 25.4% on the uninjured side, compared to a mean deficit of 9% in the control subjects. At two years post-surgery the mean activation deficits had reduced to 14.7% on the injured side and 16% on the uninjured side, although activation remained lower than in the control subjects (injured side p=0.062, uninjured side p=0.01). Importantly, it should be noted that before surgery approximately two thirds of the ACL deficient subjects exhibited greater voluntary activation deficits than the control subjects. This suggests that large activation deficits were more prevalent in these subjects when compared to those in the Urbach, Nebelung, Weiler, & Awiszus (1999) study. In addition, the results demonstrated that quadriceps voluntary activation failure can persist for long periods following ACL reconstruction, despite participation in a rehabilitation programme and a return to sporting activities.

It should be noted that both of the preceding studies demonstrated that bilateral voluntary activation deficits can occur following a unilateral ACL injury. Importantly, a more recent study by Urbach and Awiszus (2002) has investigated this phenomenon further. In this study the authors used a twitch interpolation technique to investigate the extent of bilateral voluntary activation deficits in 30 subjects with isolated ACL ruptures, 42 subjects with ACL ruptures and accompanying joint damage and 34 matched controls. The authors found that the subjects with isolated ACL ruptures exhibited mean activation deficits of 16.2% on the injured side and 14.1% on the uninjured side. In contrast, the subjects with ACL ruptures and accompanying joint damage exhibited larger deficits of 23.1% on the injured side and 22.1% on the uninjured side. In comparison, the control subjects demonstrated a mean voluntary activation deficit of 9%. Based on these findings, the authors argued that unilateral knee injuries can cause bilateral quadriceps voluntary activation deficits and that the magnitude of these deficits appears to be related to the severity of injury.

It has been suggested that a major limitation of the preceding three studies is that twitch interpolation techniques can give unreliable results if the contraction effort is not maximal or if the muscle is not fully potentiated prior to testing (Chmielewski, Stackhouse, Axe, & Snyder-Mackler, 2004). Therefore, Chmielewski et al. (2004) developed a study which provided practice and familiarization with the procedures, as well as verbal and visual encouragement, in order to ensure that the subjects were exerting a maximal effort. In this study the authors used a burst superimposition technique to assess quadriceps strength and voluntary activation in 100 consecutive subjects at an average of six weeks following isolated ACL rupture. The authors reported that mean quadriceps strength on the involved side (858.5 ± 329.4 N) was significantly lower than on the uninvolved side (989.8 ± 345.7 N). However, activation failure on the involved side ranged from 0-40% and averaged only 7.4%. This was not significantly different from activation failure on the uninvolved side which ranged from 0-42% and averaged 7.2%. In addition, using a definition of inhibition as any voluntary activation value < 95%, the authors reported that fewer than half of the subjects with inhibition exhibited activation deficits of greater than 10%. Interestingly, the authors also found that 12% of the subjects had activation failure in the involved limb only, 21% of the subjects had bilateral activation failure and, somewhat surprisingly, 10% of the subjects had activation failure in the uninvolved limb only. Thus, the cumulative incidence of quadriceps inhibition (defined as < 95% in this study) was 43% for the entire sample. For comparative purposes the authors stated that previous studies have shown the incidence of activation failure in young, healthy subjects was approximately 10%. Therefore, the authors argued that the incidence of quadriceps activation failure was higher in ACL deficient subjects compared to young healthy adults, although the magnitude of the deficits was not large in most cases. In addition, the authors suggested that the smaller activation deficits seen in this study may have been due in part to the provision of enough practice, encouragement and rest during the testing procedures to ensure that the subject's efforts were truly maximal.

In a more recent study, Williams, Buchanan, Barrance, Axe, & Snyder-Mackler (2005) also used a burst superimposition technique to investigate quadriceps activation failure in 17 subjects at an average of two months following isolated ACL rupture, although these subjects were all classified as individuals who did not compensate well for the injury. The authors reported that despite participation in a strengthening program, the quadriceps muscles of the ACL deficient limbs (1096.85 ± 279.76 N) were significantly weaker than those of the uninjured limbs (1482.06 ± 346.65 N). However, quadriceps activation deficits of only 8-10% were observed and they were not significantly different between the ACL-deficient limbs (VA 90±9%) and the uninjured limbs (VA 92±6%).

Thus, it is apparent that the findings of these two more recent studies (Chmielewski et al., 2004; Williams et al., 2005) contrasted with previous investigations (Urbach & Awiszus, 2002; Urbach et al., 2001; Urbach et al., 1999) regarding the magnitude of quadriceps activation failure in subjects with ACL deficits. These findings may in turn bring into question the relative importance of voluntary activation deficits when considering quadriceps muscle weakness in individuals with ACL deficits. Nevertheless, it appears that voluntary activation deficits play at least some role in both unilateral and bilateral quadriceps strength deficits.

Interestingly, a number of studies have been conducted to investigate a potential cause of quadriceps inhibition in ACL deficient subjects. Based on the premise that joint afferents from the ACL influence quadriceps alpha motor neuron activity (and therefore quadriceps maximum voluntary contraction) via the gamma loop, a number of studies have suggested that interruption of the gamma loop might be a potential mechanism for quadriceps weakness. For example, a succession of studies used patellar tendon vibration to continuously activate quadriceps muscle spindles and consequently reduce activity in Ia afferents (part of the gamma loop) either through neurotransmitter depletion, a heightened threshold of Ia fibres, or presynaptic inhibition of the Ia terminal. It was theorized that this would lead to a decrease in quadriceps maximum voluntary contraction (MVC) and integrated electromyogram (I-EMG) values in subjects with an intact gamma loop. Importantly, it has been reported that subjects with anaesthetized knees (Konishi, Fukubayashi, & Takeshita, 2002b), ACL deficient knees (Konishi et al., 2002b) and ACL reconstructed knees

(Konishi, Fukubayashi, & Takeshita, 2002a) exhibited abnormal responses to patellar tendon vibration suggesting that gamma loop function was compromised in these populations.

More recently gamma loop dysfunction has also been implicated in bilateral voluntary activation deficits following ACL lesions. Using patellar tendon vibration Konishi, Konishi, & Fukubayashi (2003) observed abnormal MVC and I-EMG values in the uninjured limbs of ACL deficient subjects. The authors suggested that these abnormal values provided evidence of a neurophysiological anomaly affecting the quadriceps muscle gamma loop in the uninjured limbs of ACL deficient subjects. Interestingly, the authors also proposed two possible explanations for bilateral quadriceps gamma loop deficits. The first involved the possibility that ACL lesions could cause inhibitory afferent signals to be sent to the contralateral quadriceps muscle via interneurons in the spinal cord. In contrast, the second explanation was based on studies which suggested that ACL stimulation could cause afferent feedback from mechanoreceptors to be transmitted to supraspinal central nervous system structures (Pitman, Nainzadeh, Menche, Gasalberti, & Song, 1992; Valeriani et al., 1996). Based on this premise, the authors argued it is possible that descending inhibitory signals from these structures could attenuate quadriceps muscle function bilaterally.

In conclusion, it appears that there is some disagreement in the literature regarding the size and relative importance of quadriceps voluntary activation deficits following knee injuries. However, it seems that voluntary activation deficits play at least some role in both unilateral and bilateral quadriceps strength deficits. In addition, a number of studies have suggested that altered gamma loop function may play an important role in quadriceps voluntary activation failure following ACL injury.

Importantly, a number of studies have also demonstrated large quadriceps muscle voluntary activation deficits in individuals with knee OA. For example, Hurley, Scott, Rees, & Newham (1997) measured voluntary activation in 103 subjects with knee OA and 25 control subjects by superimposing percutaneous electrical stimulation on isometric quadriceps maximal voluntary contractions. The authors reported that the subjects with knee OA exhibited a significantly ($p<0.0001$) lower median quadriceps voluntary activation value (72.5%) when compared to the control group (93%).

In another study, Hurley & Scott (1998) used the same protocol to measure quadriceps voluntary activation values in an intervention group consisting of 60 subjects with knee OA and a control group consisting of 37 subjects with knee OA. At baseline both the intervention group (73.5%; [95% CI] 44.5-85%) and the control group (72%; [95% CI] 50.5-90%) exhibited greatly reduced levels of quadriceps voluntary activation.

In a later study, Hassan, Mockett, & Doherty (2001) also superimposed percutaneous electrical stimulation on isometric quadriceps maximal voluntary contractions to measure voluntary activation in 59 subjects with knee OA and 49 control subjects. The authors reported that the subjects with knee OA demonstrated significantly ($p < 0.001$) lower levels of mean quadriceps voluntary activation (66.0%; [95% CI] 58.8-73.2%) when compared to the control subjects (87.4%; [95% CI] 80.7-94.2%). However, it is important to note that all of the subjects with OA were symptomatic and were recruited from a hospital based population, increasing the likelihood that they represented the more severe end of the knee OA spectrum.

Interestingly, Fitzgerald, Piva, Irrgang, Bouzubar, & Starz (2004) found much smaller deficits than those previously described when using a burst superimposition technique to measure isometric quadriceps voluntary activation in 105 subjects with radiographically confirmed knee OA. The reported mean activation deficit for the OA subjects was 3.5% ± 5.0 (SD) with a range of 0-38%. However, it should be noted that a knee flexion angle of 60º was used for the isometric testing, which differs from the 90º angle used in many other studies (Hassan et al., 2001; Hurley & Scott, 1998; Hurley et al., 1997; Pap et al., 2004). In addition, the study lacked a control group for comparative purposes. However, despite the small mean activation deficit observed in this group, the authors stated that their overall results showed a similar profile to those of Hassan et al. (2001) and Hurley et al. (1997) in that the relationship between quadriceps strength and physical function was moderated by the degree of quadriceps voluntary activation failure. The authors argued that these similarities suggested the same phenomena were being measured in these studies, although the variation in the magnitude of the activation deficits highlighted the problem of comparing studies which used different stimulus parameters and testing procedures.

A more recent study by Pap, Machner, & Awiszus (2004) investigated quadriceps voluntary activation in subjects with different levels of OA degeneration. Isometric quadriceps voluntary activation was measured using a twitch interpolation technique in 68 subjects with Outerbridge (1961) stage II (mild) OA, 154 subjects with stage IV (severe) OA and 85 age matched controls. The authors reported that mean quadriceps activation was significantly higher in the control group (89.3% ± 8.0, range 55.4–98%) than in both of the OA groups (p <0.001). However, when the authors compared the OA groups they found that the subjects with stage IV OA actually had significantly higher (p=0.004) activation values (77.2% ± 13.2, range 37.5–97.5%) than the subjects with stage II OA (70.8% ± 16.0, range 4.5–97.3%). This result is somewhat surprising since conventional thinking would suggest that increasing levels of joint degeneration might lead to concomitant reductions in quadriceps voluntary activation. However, Pap, Machner, & Awiszus (2004) argued that these findings do not necessarily conflict with those of previous studies because those investigations did not specifically assess differing severities of joint damage. Instead, previous studies generally examined the associations between activation deficits, strength deficits and differing degrees of disability, which Pap, Machner, & Awiszus (2004) argued do not necessarily correlate with the severity of joint damage. Nevertheless, an explanation of why quadriceps voluntary activation might be greater in individuals with more severe levels of joint degeneration remains elusive. However, based on the premise that knee OA initially causes joint receptors to generate afferent signals which inhibit quadriceps activation, it could be argued that more severe joint degeneration might eventually render these receptors inactive and therefore reduce the flow of inhibitory signals. In addition, it is possible that confounding factors specific to this study may have influenced the results. For example, the number of subjects in the stage II OA group was considerably smaller than the stage IV group and the range of voluntary activation values for the stage II group was wider, with one subject exhibiting a quadriceps activation deficit of 95.5% (Pap et al., 2004). In addition, the Outerbridge (1961) classifications create specific subsets of OA subjects which may not be representative of those with mild or severe OA as a whole (Pap et al., 2004).

Finally, in a recent study Molloy (2005) measured voluntary activation using a twitch interpolation technique in 26 subjects with unilateral knee OA (mean age 63.6 ± 12.51 years) and 17 control subjects (mean age 64.69 ± 9.52 years). For the subjects with knee OA, the author reported mean voluntary activation deficits of 10.6% (± 9.4) and 8.2% (± 7.2) in the affected and unaffected limbs, respectively. In contrast, the author reported a mean voluntary activation deficit of just 1.0% (± 2.1) for the control subjects. Based on these findings, the author stated that the subjects with unilateral knee OA exhibited significant bilateral voluntary activation deficits when compared to the control subjects ($p < 0.05$).

In conclusion, it appears that a number of studies have demonstrated that quadriceps voluntary activation failure can occur following the onset of knee OA. In turn, these findings may partially explain the quadriceps strength deficits that are so frequently seen in individuals with knee OA.

Quadriceps Muscle Atrophy

While pain, joint effusion and activation failure appear to influence quadriceps muscle strength primarily through neural inhibition, it seems likely that if sustained, these phenomena could lead to quadriceps muscle atrophy. This is important because maximum effort muscle torque has been shown to be closely correlated to changes in muscle volume. Therefore, atrophic changes in a muscle could result in concomitant reductions in strength (Fukunaga et al., 2001).

A number of studies have demonstrated that quadriceps atrophy can occur in individuals with knee injuries. For example, Gerber, Hoppeler, Claassen, Robotti, Zehnder, & Jakob (1985) investigated quadriceps atrophy using computed tomography in 41 subjects with chronic, symptomatic instability of the ACL. The authors reported that there was an overall atrophy of approximately 8% in quadriceps cross sectional area (CSA) compared to the uninvolved limb. In addition, they found that the relative decrease in the CSA of the vastus medialis was 2.7% greater than the relative decrease in the total CSA of the quadriceps muscle.

In a more recent study, Williams, Buchanan, Barrance, Axe, & Snyder-Mackler (2005) measured quadriceps volume and CSA in 17 “non-copers” with isolated ACL injuries. The authors reported mean atrophy of approximately 9% in the affected quadriceps muscles, although in this study the vastus lateralis and vastus intermedius muscles were found to be disproportionately affected. The authors suggested that as the largest muscles of the quadriceps group, the vastus lateralis and vastus intermedius muscles may be more vulnerable to the neural disruption that occurs when the ACL is ruptured. Importantly, the authors also reported that quadriceps strength in the ACL deficient limbs was significantly lower (average 25%) than in the uninjured limbs and that atrophy, along with an average activation failure level of 10%, explained more than 60% of the variance in quadriceps weakness ($p = .004$).

In a study of meniscal injuries, Akima & Furukawa (2005) investigated thigh muscle atrophy in 32 subjects following meniscal lesions and arthroscopic partial meniscectomy. Using magnetic resonance imaging the authors found that quadriceps muscle volume was significantly lower (approximately 13.5%) in the involved leg compared to the uninvolved leg. However, in contrast to Williams et al's (2005) and Gerber et al's (1985) findings, the authors reported that the atrophy seemed to be relatively uniform across the four heads of the quadriceps muscle.

Interestingly, some studies have also suggested that knee osteoarthritis and certain knee injuries may cause preferential atrophy of different muscle fibre types. For example, Nakamura, Kurosawa, Kawahara, Watarai, & Miyashita (1986) used biopsies from the vastus lateralis muscle to investigate muscle fibre atrophy in 51 subjects with isolated ACL injuries, 29 subjects with combined ACL and meniscus injuries, 25 subjects with isolated meniscal injuries and 7 subjects with isolated collateral ligament injuries. The authors reported that atrophy of type 2 fibres occurred in all four conditions, while atrophy of type 1 fibres occurred only in subjects with isolated ACL or combined ACL and meniscal injuries. Based on these results, the authors argued that the atrophy of type 2 fibres could be a non-specific change related to muscle disuse, while the atrophy of type 1 fibres could be a specific adaptation related to disruption of the ACL.

Nakamura & Suzuki (1992) also used vastus lateralis muscle biopsies to compare fibre atrophy in 27 females with knee OA and 16 females with lower extremity fractures. The authors reported that type 2 fibre atrophy was found in both groups but was more frequent in the OA group. In addition, the authors found abnormal mosaic patterns of fibre types (such as fibre type grouping and grouped atrophy of type 2 fibres) more frequently in the knee OA subjects (73.1%) and less frequently in the subjects with fractures (6.3%).

In a more recent study, Molloy (2005) collected surface electromyography (sEMG) data from the vastus medialis muscles of 26 subjects with unilateral knee OA during an isometric endurance test. The author reported that the initial values for median frequency and mean power frequency were significantly lower in the affected limb compared to the unaffected limb ($p < 0.05$). Importantly, the author suggested that a key contributing factor to these differences might be a decrease in the proportions of type 2 muscle fibres in the vastus medialis of the affected leg. However, the author also cautioned that many factors can influence sEMG values and therefore care should be exercised when making assumptions about fibre type distributions based on sEMG amplitude, spectral and conduction velocity measures alone.

While some studies have suggested that knee OA and specific types of knee injuries may cause preferential atrophy of different muscle fibre types, other studies have suggested that atrophy may be relatively uniform across fibre types. For example, Gerber et al. (1985) examined biopsies from the vastus lateralis muscles of 41 subjects with chronic symptomatic instability of the ACL and reported a similar decrease in fibre size for all fibre types. In addition, Tho, Nemeth, Lamontagne, & Eriksson (1997) examined the quadriceps muscles of 15 subjects at 4 to 24 months post ACL rupture and determined that both type 1 and type 2 fibres exhibited a similar level of atrophy, although these findings were based on EMG frequency analysis rather than muscle biopsies.

In conclusion, it appears that quadriceps muscle atrophy can occur frequently in subjects with knee injuries and knee OA and might therefore contribute to quadriceps weakness in these populations. However, it is less clear whether these pathologies lead to preferential atrophy of different muscle fibre types.

Immobilization and Disuse

It has been demonstrated that immobilization or disuse of a limb can lead to muscle weakness (Berg, Larsson, & Tesch, 1997; Hortobagyi et al., 2000). This is important because immobilization may be used as part of the treatment regime following a knee injury and because relative disuse of a limb is not uncommon with knee injuries or knee OA. A number of factors may contribute to muscle weakness following immobilization/disuse including alterations in the muscle's non-contractile and contractile elements and reductions in voluntary activation levels.

Studies using animals by Järvinen, Józsa, Kannus, Järvinen, & Järvinen (2002) and Jozsa, Kannus, Thoring, Reffy, Jarvinen, & Kvist (1990) have demonstrated that immobilization can cause significant alterations in intramuscular connective tissue including proliferation and thickening of connective tissue, irregular collagen orientation and dramatic reductions in capillary numbers. These studies also showed that increases in connective tissue can occur around the remaining intramuscular capillaries, separating them from individual muscle fibres. In turn, the authors proposed that such a connective tissue barrier, in combination with an overall reduction in capillary numbers, could significantly disrupt blood supply to the muscle fibres and consequently accelerate muscle fibre atrophy.

A number of studies have also described atrophic changes in the contractile elements of muscles following immobilization. These include general muscle fibre atrophy, preferential atrophy of different fibre types and transformations between fibre types.

With respect to general fibre atrophy, Young, Hughes, Round, & Edwards (1982) investigated the number and size of quadriceps muscle fibres in 14 subjects with observable thigh muscle wasting secondary to knee injury. The authors reported that the atrophy seen in these subjects was primarily due to a decrease in muscle fibre CSA. Berg, Larsson & Tesch (1997) also observed reductions in muscle fibre CSA (mean 18% ± 14) in the vastus lateralis muscles of seven healthy males after six weeks of bed rest. In a more recent study, Hortobagyi, Dempsey, Fraser, Zheng, Hamilton, Lambert, & Dohm (2000) described declines in vastus lateralis muscle fibre CSA in 48 healthy subjects following 3 weeks of immobilization at 3º of knee flexion. The authors found that type 1, 2a and 2x muscle fibre areas were significantly and uniformly reduced by 13%, 10% and 10%, respectively. However, while these studies found that atrophy was primarily due to a decrease in fibre CSA, a study by Halkjaer-Kristensen & Ingemann-Hansen (1985) found that quadriceps atrophy following knee collateral ligament rupture and one month of immobilization was due, in part, to a 28% loss in the *number* of vastus lateralis muscle fibres. In any case, all of these studies may have limitations. For example, it is possible that the biopsied fibres were not representative of those in the other heads of the quadriceps muscle or even in the rest of the vastus lateralis muscle, either at the same level or along the length of the muscle. In addition, atrophic changes in fibre orientation or fibre length may have influenced the biopsy results (Halkjaer-Kristensen & Ingemann-Hansen, 1985; Young et al., 1982). Nevertheless, these studies appear to have consistently demonstrated that muscle fibre CSA was significantly reduced following a period of immobilization/disuse.

While general muscle fibre atrophy has been demonstrated following immobilization and disuse, it is less clear whether preferential atrophy of different fibre types occurs under these conditions. Preferential atrophy of different fibre types may be important when considering strength deficits because the contractile and energetic properties of type 1 and type 2 muscle fibres differ depending on their myosin heavy chain (MHC) isoform content. Type 1 fibres contain the MHC-1 isoform and have lower maximum shortening velocity, maximum power and ATPase activity than type 2 fibres (D'Antona et al., 2006). In addition, the specific tension developed by type 2 fibres has generally been shown to be greater than that of type 1 fibres (Bottinelli & Reggiani, 2000).

A number of studies have suggested that type 1 fibres are preferentially affected by immobilization. Sargeant and Davies Edwards, Maunder, & Young (1977) investigated muscle atrophy in the vastus lateralis muscles of seven subjects following unilateral leg fracture and immobilization and found a trend towards greater atrophy of type 1 (46%) than type 2 (37%) fibres. In addition, Häggmark, Jansson, & Eriksson (1981) investigated quadriceps muscle atrophy following knee surgery and five weeks of immobilization and found that there was preferential atrophy of type 1 fibres (26.5%, $p<0.0025$) but no significant change in the average size of type 2 fibres. Finally, in a more recent study Halkjaer-Kristensen & Ingemann-Hansen (1985) found that there was preferential atrophy of type 1 fibres in the vastus lateralis muscle (21%, $p<0.001$) following knee collateral ligament rupture and one month of immobilization. However, it should be noted that in all of these studies the subjects had some form of lower extremity injury and therefore the effects of immobilization were not examined in isolation.

In direct contrast to studies that have described preferential atrophy of type 1 fibres, at least one investigation appears to have demonstrated greater atrophy of type 2 fibres following immobilization. Yasuda, Glover, Phillips, Isfort, & Tarnopolsky (2005) examined sex based differences in vastus lateralis muscle morphology by taking biopsies from 27 healthy subjects following 14 days of immobilization in a knee brace (60º knee flexion).The authors reported that the decreases in type 1 (Male = 4.8% ± 5.0, Female = 5.9% ± 3.4), type 2a (Male = 7.9% ± 9.9, Female = 8.8% ± 8.0) and type 2x (Male = 10.7% ± 10.8, Female = 10.8% ± 12.1) fibre areas were similar for both sexes. However, while not explicitly discussed by the authors, these results also appeared to show that there was greater atrophy of type 2 fibres compared to type 1 fibres under the immobilization conditions used in this study.

Despite the arguments that preferential atrophy of different fibre types occurs, some studies have indicated that type 1 and type 2 muscle fibres may be affected by immobilization in a relatively uniform manner. For example, Veldhuizen, Verstappen, Vroemen, Kuipers, & Greep (1993) examined biopsies from the vastus lateralis muscles of 8 healthy subjects following 4 weeks of cast immobilization and reported no significant difference in the level of type 1 and type 2 fibre atrophy ($p > 0.05$). In a study described previously, Hortobagyi et al. (2000) also reported that type 1, 2a and 2x fibre areas in the vastus lateralis muscle were uniformly reduced by 13%, 10% and 10%, respectively, following 3 weeks of immobilization at 3º of knee flexion.

As with the lack of agreement regarding the preferential atrophy of different fibre types, there appears to be some disagreement in the literature over fibre type transformations following immobilization. For example, Jankala, Harjola, Petersen, & Harkonen (1997) found that hind-limb immobilization for one week significantly altered the MHC mRNA profile in rat soleus, gastrocnemius, and plantaris muscles towards faster isoforms. In addition, Andersen, Gruschy-Knudsen, Sandri, Larsson, & Schiaffino (1999) observed changes at the mRNA and protein level in the vastus lateralis muscles of 7 male subjects following 37 days of bed rest. The authors reported that muscle biopsies demonstrated a mismatch between MHC isoforms involving an increase in the number of fibres expressing mRNA for MHC-2x and a decrease in the number of fibres expressing mRNA for MHC-1, without significant changes at the protein level. Based on these results, the authors suggested that an increase had occurred in the amount of muscle fibres in a transitional state from phenotypic type 1→2a and 2a→2x. However, in contrast to these studies at least one investigation has failed to find evidence of fibre transformation. In a study described earlier, Yasuda, Glover, Phillips, Isfort, & Tarnopolsky (2005) reported that following 14 days of immobilization in a leg brace, muscle biopsies from the vastus lateralis muscles showed no significant changes in the percentage distribution of type 1, type 2a and type 2x fibres and therefore no evidence of fibre transformation.

Despite the lack of agreement in the literature over the preferential atrophy of different fibre types and the occurrence of fibre type transformations, it is evident from the studies described above that significant atrophy can occur in quadriceps muscle fibres following immobilization under a variety of conditions. Importantly, it has also been demonstrated that quadriceps atrophy following immobilization is associated with significant reductions in maximal voluntary strength. For example, Berg, Larsson, & Tesch (1997) reported that after 6 weeks of bed rest a 13.8% (± 4.5%) reduction in quadriceps femoris CSA was accompanied by a 24.5% (± 10.5%) reduction in maximum isometric torque and a 28.9% (± 12.2%) reduction in maximum concentric torque. Hortobagyi et al. (2000) also reported that an 11% reduction in quadriceps CSA was correlated (r=0.75) with a 47% loss of isometric, concentric and eccentric quadriceps strength. Finally, Thom, Thompson, Ruell, Bryant, Fonda, Harmer, De Jonge, & Hunter (2001) found that an 11.8% reduction in quadriceps CSA was accompanied by a 41.6% reduction in 1-RM leg extension strength following cast immobilization from the hip to the ankle for 10 days.

However, while the studies described above demonstrated that a relationship existed between decreased quadriceps muscle CSA and diminished knee extensor strength following immobilization, it should also be recognized that the reductions in strength greatly exceeded those in muscle CSA. Importantly, some authors have proposed that alterations in neural activity following immobilization may explain these discrepancies. For example, Kawakami, Akima, Kubo, Muraoka, Hasegawa, Kouzaki, Imai, Suzuki, Gunji, Kanehisa, & Fukunaga (2001) measured quadriceps activation in 4 subjects who underwent head down bed rest only and in 5 subjects who underwent head down bed rest but also performed a daily bilateral isometric leg extension exercise. While there was no significant difference between the groups before bed rest, the authors reported that quadriceps voluntary activation (VA) was reduced in all subjects in the non-exercise group following bed rest (VA range: 78% to 82%). In contrast, quadriceps activation in the exercise group remained relatively unchanged (VA: range 87% to 96%). Importantly, the authors also reported that the reduction in quadriceps activation in the non-exercise group was correlated with a 10.9% (± 6.9) decease in isometric quadriceps strength. Based on these results, the authors argued that, in the non-exercise group, the reduction in strength following bed rest was influenced by a decreased ability to neurally activate quadriceps muscle motor units.

In a more recent study, Mulder, Stegeman, Gerrits, Paalman, Rittweger, Felsenberg, & de Haan (2006) also investigated changes in quadriceps CSA, maximal strength and neural activation in 9 subjects who underwent bed rest only and in 9 subjects who underwent bed rest and resistive vibration exercise. The authors reported that quadriceps CSA (-14.1% ± 5.2) and maximal isometric torque (-16.8% ± 7.4) decreased significantly in the bed rest only group but not in the exercise group. However, maximal voluntary activation (measured seven times) did not change in either group throughout the study. Importantly, the authors suggested that the lack of change in activation might have been due to the repeated testing of muscle function during the bed rest period. The authors supported this contention by reporting that in a subgroup of 5 bed rest only subjects, maximal voluntary torque in the otherwise untested left leg decreased by twice as much compared to the right leg (20.5% vs. 11.1%) and did not equate with the loss of CSA in the left and right legs (11% vs. 9%). Based on these findings, the authors argued that neural activation may have diminished in the more fully immobilized left leg because the decrease in torque could not be completely explained by the reduction in quadriceps CSA.

In conclusion, it is apparent from the studies reviewed here that immobilization or disuse can result in significant reductions in maximal quadriceps strength. In turn, these declines in strength are thought to be largely due to atrophic physiological and structural changes within the muscle, as well as reductions in voluntary activation.

Summary

The studies reviewed above have generally demonstrated that factors such as pain, joint effusion, activation failure, atrophy and immobilization/disuse can lead to reductions in maximal voluntary muscle strength. Consequently, these phenomena are likely to contribute to the large quadriceps strength deficits that are often observed in individuals with knee injuries and knee OA. In turn, it seems likely that quadriceps weakness could reduce the prospect of returning to pre-injury activity levels and lead to varying degrees of disability. Therefore, these issues will be discussed briefly in the following two sub-sections.

2.3.1.4. Knee Injuries, Quadriceps Deficits and Return to Sport

A number of studies have reported that some individuals are unable to return to their previous level of sporting activity following significant knee injuries. For example, Roos, Ornell, Gardsell, Lohmander, & Lindstrand (1995) investigated return to sport following ACL injury in 778 soccer players and reported that only 30% of the ACL injured subjects were active in soccer after three years, compared to 80% of subjects in a control population. In addition, the authors reported that no elite players with ACL injuries were active at their previous levels after seven years. In a follow-up study involving a subgroup of 154 males from the original sample, von Porat, Roos, & Roos (2004) reported that only 12 subjects (7.8%) were still playing organized soccer at 14 years post-injury. In addition, the authors reported that only 28 subjects (18%) scored “excellent” in the sport/recreation section of the Knee Injury and Osteoarthritis Outcome Score (KOOS) questionnaire. In a another follow-up study involving 84 females from the original sample, Lohmander, Östenberg, Englund, & Roos (2004) reported that more than 50% of the subjects never returned to organized soccer and only 8% were still playing at 12 years post-injury. In addition, at 12 years post-injury the authors reported that large differences were observed between the injured group and an uninjured reference group in the sport/recreation section of the KOOS questionnaire, with mean scores of 54 and 89, respectively.

In a study of handball players, Myklebust, Holm, Maehlum, Engebretsen, & Bahr (2003) investigated return to sport following ACL injury in 79 elite players, 22 of whom were treated conservatively and 57 of whom were treated surgically. At an average follow-up time of 7.1 years (range 6 to 8 years), the authors reported that in the conservatively treated group, 18 subjects (82%) returned to their previous level of team handball, two subjects returned to a lower level and two subjects did not play again. For the surgical group, the authors reported that 33 subjects (58%) returned to the same level, 17 (30%) returned at a lower level and seven never played again.

In contrast to the studies described above, some investigations have described excellent return to sport results following ACL reconstruction. From an original sample of 1231 ACL reconstructed subjects, Shelbourne & Gray (2000) obtained subjective follow-ups regarding return to sport for 928 subjects at an average of 8.6 (±2.5) years after surgery. The authors analysed the results by associated meniscal surgery and reported that 97% of subjects (466) with intact menisci had returned to sport at or above their previous level. In addition, the authors reported that 88% of subjects (156) with associated medial meniscectomy, 91% of subjects (148) with associated lateral meniscectomy and 84% of subjects (91) with associated bilateral meniscectomy had returned to sport at or above their previous level.

Despite reporting good return to sport results, a more recent study has also provided some caveats. Smith, Rosenlund, Aune, MacLean, & Hillis (2004) stated that from an original group of 109 competitive athletes who underwent ACL reconstruction, 77 responded to a follow-up questionnaire at an average of 43 months post-surgery. The authors reported that 62 subjects (81%) had returned to competition within 12 months of surgery and that 55 of these subjects had returned at their previous level or better. However, at the time of completing the questionnaire, only 47 of the original 77 subjects were still involved in competitive sport and only 30 of the 55 subjects who had returned to their previous level of sport were still competing at this level. In addition, the authors reported that the overall incidence of subjects competing despite complaints of major functional impairment in the operated knee was 13 of 62 (21%) at 12 months and six of 47 (13%) at follow up. Thus, it appears that some individuals were unable to maintain their return to competitive sport over extended periods of time, while others returned to sport despite ongoing knee problems.

Importantly, some studies have suggested that achieving a minimum level of quadriceps strength might influence an individual's ability to return to sport. For example, Eastlack, Axe, & Snyder-Mackler (1999) reported that 12 ACL deficient subjects who had returned to their previous level of sport exhibited significantly greater average isometric quadriceps strength than 33 ACL deficient subjects who had not returned to their previous level of sport ($p < 0.01$).

In another study using ACL deficient subjects, Rudolph, Axe, & Snyder-Mackler (2000) measured isometric quadriceps strength in 11 high level athletes who had successfully returned to sport and 10 high level athletes who had not returned to sports and were experiencing knee instability with daily activities. The authors reported that isometric quadriceps strength indices were considerably higher in the 11 subjects who returned to sport (mean 97.1 ± 12.7%; range 74.8% to 126%), than in the 10 subjects who did not (mean 75.3±11.3%; range 62.4% to 97.3%; $p = 0.001$).

In a study designed primarily to compare two different quadriceps strengthening programs, Mikkelsen, Werner, & Eriksson (2000) measured isokinetic peak torque in 44 ACL reconstructed subjects. The authors reported that subjects ($n = 22$) who performed both open and closed chain exercises increased their concentric and eccentric quadriceps peak torque significantly more than subjects ($n = 22$) who performed only closed chain exercises. The reported mean percentage values for injured vs. uninjured knee strength ranged from 81.2% to 89% for the combined exercise group and from 65.7% to 75.6% for the closed chain exercise group. In addition, the authors reported that 12 subjects from the group with greater quadriceps torque were able to return to their previous level of sport after a median of 7.5 (± 1) months, while only 5 subjects from the group with lower quadriceps torque were able to return to their previous level of sports at a median of 9.5 (± 3) months.

In a more recent study, Cardone, Menegassi, & Emygdio (2004) also investigated quadriceps strength and return to sport. The authors measured isokinetic quadriceps peak torque in 67 ACL reconstructed subjects at angular velocities of 60º/s, 180 º/s and 240º/s and reported differences of 25%, 17% and 12%, respectively, between the reconstructed and uninjured knees at six months post-surgery . In addition, the authors reported that all subjects had returned to sporting activity without difficulty by six months post-surgery. Based on these findings, the authors suggested that quadriceps strength in the ACL reconstructed limb should reach at least 75% of that in the uninjured limb (at an angular velocity of 60º/s), before individuals return to sport. In addition, if the strength values are averaged across all three velocities, the results suggest that quadriceps strength in the ACL reconstructed limb should reach at least 82% of that in the uninjured limb before individuals return to sport. Importantly, this finding appears to be consistent with the range of strength values (81.2% to 89%) reported by Mikkelsen, Werner, & Eriksson (2000) for the group of ACL reconstructed subjects who had the best return to sport results. Finally, these values also appear to be consistent with a recent review by Kvist (2004) which recommended that quadriceps strength in an ACL injured limb should reach at least 85% of that in an uninjured limb before a return to sport is allowed.

In conclusion, it appears that quadriceps strength may influence return to sport in some individuals with knee injuries and that a side to side difference of greater than 15% may reduce the likelihood of a successful return to sport. However, it should also be recognized that many other factors such as joint laxity, effusion, diminished proprioception, reduced endurance and psychological issues might also influence an individual's ability to successfully return to their previous level of sport (Kvist, 2004).

2.3.1.5. Knee OA, Quadriceps Deficits and Function

It has been demonstrated that knee OA is one of the most common causes of disability in community dwelling older adults, leading to difficulties with activities such as stair climbing, walking, housekeeping and carrying objects (Guccione & Felson, 1994). Importantly, it has also been shown that quadriceps weakness is associated with reduced functional performance in some older adults. For example, in two studies of healthy older adults, Hyatt, Whitelaw, Bhat, Scott, & Maxwell (1990) and Rantanen, Era, & Heikkinen (1994) demonstrated significant associations between maximal isometric quadriceps strength and various measures of lower limb functional performance and ambulation. Additionally, in a more recent study using 100 healthy older adults, Ploutz-Snyder, Manini, Ploutz-Snyder, & Wolf (2002) demonstrated significant relationships between various functional activities and the ratio of isometric knee extension peak torque to body weight. The authors reported that individuals with a quadriceps strength/weight ratio < 3.0 Nm/kg were at substantial risk for impaired function in gait speed, ascending and descending stairs and rising from a chair. In addition, the authors reported that the sensitivity and specificity of the quadriceps strength/weight ratio as a predictor of functional performance ranged from 76% to 81% and from 78 to 94%, respectively, depending on the task. Therefore, it could be argued that one of the mechanisms which might contribute to reduced functional performance in individuals with knee OA is the frequently occurring problem of quadriceps muscle weakness. Further evidence to support this hypothesis comes from a study by Steultjens, Dekker, van Baar, Oostendorp, & Bijlsma (2001) who investigated the relationship between muscle strength and disability in subjects with OA of the hip and knee. The authors measured maximal isometric muscle strength for 16 muscle actions around the knees and hips of 52 subjects with hip OA and 70 subjects with knee OA and reported that isometric muscle strength was negatively associated with disability (i.e. greater strength deficits were associated with more disability). In addition, the authors reported that variations in muscle strength were found to account for approximately 15-20% of the variance in disability. Based on these findings, the authors suggested that muscle strength is an important determinant of disability in OA of the knee and hip. However, it should be recognized that many factors other than muscle strength also appear to contribute to the incidence of disability in individuals with knee OA including pain, joint stiffness, obesity, depression, anxiety and lack of self-efficacy (Maly, Costigan, & Olney, 2006; Rejeski, Craven, Ettinger, McFarlane, & Shumaker, 1996; Sharma, Cahue et al., 2003). For example, in a recent review Sharma Kapoor & Issa (2006) suggested that a close relationship may exist between muscle strength, pain and self-efficacy in their effect on physical functioning in knee OA. The authors argued that knee pain and muscle weakness might result in activity modification or avoidance which in turn could lead to diminished self-efficacy and ultimately physical disability. Importantly, factors such as joint stiffness, obesity, depression and anxiety might also be incorporated into such a model.

In conclusion, it appears likely that the significant quadriceps strength deficits frequently observed in subjects with knee OA contribute to physical disability in some individuals.

2.3.1.6. Section Summary

This section has presented discussions regarding knee injuries and knee OA with respect to three main themes. Firstly, evidence was provided which suggests that large and enduring quadriceps strength deficits can occur following knee injuries and the onset of OA. Secondly, it was argued that mechanisms such as pain, effusion, voluntary activation failure, atrophy and immobilization are likely to contribute to these deficits. Finally, it was suggested that quadriceps strength deficits might lead to reduced levels of recreational and functional activity in individuals with knee injuries and knee OA.

2.4. RESISTANCE TRAINING

It was established in the preceding section that quadriceps muscle weakness is common in individuals with knee injuries and knee OA. Therefore, reliable and valid methods of measuring maximal strength would appear to be essential for identifying and quantifying muscle weakness in these populations. In addition, accurate measurements of muscle strength might be useful for planning appropriate therapeutic interventions and monitoring subsequent improvements or deteriorations in strength. A commonly used therapeutic intervention for developing musculoskeletal strength is resistance training (Kraemer et al., 2002). With respect to physiotherapy, this assertion has been supported by a survey of treatment techniques conducted by Jette & Delitto (1997) which showed that up to 87% of treatments for knee problems included strengthening exercises. However, it is unclear whether the "strengthening" exercises described in this survey were consistent with the principles of progressive resistance training. Indeed it appears that, at least anecdotally, "strength" training may often take place in clinical settings without an assessment of baseline maximal strength or with strength measures that are established using potentially inaccurate testing procedures (Bohannon, 2001; Bohannon, 2005; Dvir, 1997; Hayes, Walton, Szomor, & Murrell, 2002). Additionally, a study by Glass & Stanton (2004) demonstrated that when healthy individuals unfamiliar with resistance training self-selected exercise loads, they consistently chose relatively low weights ranging from 42% to 57% of their 1-RM. In turn, it seems likely that individuals with joint pathology might select even lower levels of resistance under similar conditions if they were fearful of re-injury or exacerbating their symptoms. Issues such as these are particularly important because resistance training loads are thought to play a critical role in determining many of the beneficial adaptations that occur with resistance exercise, including improvements in strength, power, local muscular endurance and motor performance (Bird, Tarpenning, & Marino, 2005; Fry, 2004; Kraemer et al., 2002; Kraemer & Ratamess, 2004). For example, with respect to strength it has been suggested that, in healthy populations, the initial gains (6-12 weeks) associated with resistance training come primarily from adaptations in the neural regulation of muscle activity (Behm, 1995; Bird et al., 2005). These changes include enhancements in the recruitment, firing frequency and synchronization of motor units, as well as reflex potentiation and alterations in both the co-contraction of antagonist muscles and the activation of synergist muscles (Behm, 1995; Bird et al., 2005). Although loads ≤ 50% of 1-RM have been shown to improve strength in untrained individuals during this motor learning phase, it has been suggested that greater loads may be more effective (Campos et al., 2002; Stone & Coulter, 1994; Weiss, Coney, & Clark, 1999). In addition, as strength and training experience progress, greater loads may actually be required to elicit further neural adaptations including the activation of high-threshold motor units (Kraemer et al., 2002). For example, the results of a recent meta-analysis by Rhea, Alvar, Burkett, & Ball (2003) suggested that untrained individuals (less than one year of consistent training) achieved maximal gains with a mean training intensity of 60% of their 1-RM, while trained individuals experienced the greatest strength increases with a mean intensity of 80% of their 1-RM.

While neural changes appear to be the primary mechanism for strength increases in the early phases of resistance training, it is generally accepted that muscle fibre hypertrophy plays a significant role in the later phases (> 12 weeks) (Bird et al., 2005; Fry, 2004). As with neural adaptations, hypertrophy is thought to be influenced by the loads used during resistance training (Bird et al., 2005; Kraemer et al., 2002). It has been suggested that loads corresponding to 70-80% of 1-RM are typically used in training programs designed to target hypertrophy (Kraemer et al., 2002), although some studies have demonstrated that both heavier and lighter loads can also lead to increases in muscle fibre CSA (Campos et al., 2002; Moss, Refsnes, Abildgaard, Nicolaysen, & Jensen, 1997).

In contrast to training programs designed to increase maximum strength, it has been suggested that protocols intended to enhance muscle power should incorporate a combination of lighter loads (30-60% of 1-RM) lifted at explosive velocities and heavier loads (85-100% of 1-RM) lifted at slower velocities because these loading strategies are thought to increase fast force production and overall force, respectively (Kraemer et al., 2002). In addition, it has been argued that training programs designed to augment local muscular endurance should also differ from traditional strength training programs, with a number of authors suggesting that low loads coupled with high repetitions may be the optimal method for increasing endurance (Campos et al., 2002; Kraemer et al., 2002; Stone & Coulter, 1994; Weiss et al., 1999). Finally, it has been suggested that in order to optimize overall muscle function and improve motor performance for specific functional or athletic endeavours, a combination of loading strategies is likely to be required (Crewther, Cronin, & Keogh, 2005; Cronin, McNair, & Marshall, 2003b; Kraemer & Ratamess, 2004).

In conclusion, it is apparent that an accurate assessment of muscle strength is critical for identifying and quantifying quadriceps weakness in individuals with knee injuries and knee OA. In addition, an accurate measurement of quadriceps strength could be used to determine effective baseline loads and load progressions, not only for programs that are intended to address muscle weakness, but also for interventions aimed at improving factors such as power, muscular endurance and motor performance (Bird et al., 2005; Fry, 2004; Kraemer et al., 2002). Finally, an accurate, safe and easily applied method of testing maximal muscle strength could prove to be a valuable tool for monitoring changes in strength during the rehabilitation of individuals with knee injuries or knee OA. Therefore, a review of the procedures that can be used to assess quadriceps muscle strength follows.

2.5. TECHNIQUES FOR ASSESSING MUSCLE STRENGTH

A variety of techniques for measuring maximal muscle strength are available to healthcare practitioners including manual muscle testing (MMT), isometric dynamometry, isokinetic dynamometry, muscle girth/CSA measurements and functional performance testing. However, with respect to traditional weight training equipment it appears that the most commonly used measure of maximal strength is the one repetition maximum (1-RM) (Brown & Weir, 2001). When considering the clinical utility of the 1-RM test it is important to evaluate factors such as its reliability, validity, sensitivity and the practicality of using it in a clinical setting. Therefore, these issues will be discussed in the following section. However, when considering the reliability of this procedure it should be noted that many studies have only reported correlation coefficients as evidence of test-retest reliability. Although these statistics may provide an indication of "relative reliability", it has been suggested that other statistical procedures (e.g. Bland and Altman analysis, coefficient of variation) are required to demonstrate "absolute reliability" (Atkinson & Nevill, 1998). Therefore, the results of these studies should be viewed with caution.

2.5.1. Isoinertial 1-RM Testing

Isoinertial strength testing involves lifting external loads of constant value through a predetermined range of motion (ROM). The 1-RM is the maximum load that can be lifted with proper technique for only one repetition (Brown & Weir, 2001; Kroemer, 1999; Pereira & Gomes, 2003). However, it should be recognized that during isoinertial testing the velocity of the movement and the mechanical conditions affecting the muscles (e.g. muscle length/pull angles/lever arms) are subject to change, resulting in variable levels of force production throughout the ROM (Kroemer, 1999). As a consequence, the 1-RM has been criticised because the muscles being tested may be performing sub-maximally throughout much of the movement and because the maximum load that can be lifted will be limited by the point in the ROM at which force production is lowest (Brown & Weir, 2001). In addition, the correlation between 1-RM strength and the ability to perform many functional and athletic activities has been questioned due to differences between these tasks with respect to movement velocities, movement accelerations, movement patterns and muscle contraction modes (Brown & Weir, 2001). However, such an argument could be made against all of the strength testing procedures described in this section. In addition, as Cronin, McNair, & Marshall (2003a) perceptively observed, it is unlikely that any single strength measure could adequately express or provide insight into all the mechanisms required for the optimal performance of a functional or athletic endeavour. Instead, it seems likely that a valid and reliable measure of muscle strength might be best utilized as a single component in a battery of tests aimed at assessing the key elements required for the optimal performance of the task in question. In fact, the 1-RM has been supported as an appropriate method of measuring muscle strength by the American College of Sports Medicine (2005) and has been described as one of the most frequently used tests of maximum muscle strength, at least in healthy populations (Braith, Graves, Leggett, & Pollock, 1993; Brown & Weir, 2001; Brzycki, 1993; Chapman, Whitehead, & Binkert, 1998; Ploutz-Snyder & Giamis, 2001). The 1-RM has also been shown to be sensitive to changes in strength during both upper and lower extremity resistance training programs

(Abernethy & Jurimae, 1996; Kraemer et al., 2004; Rhea, Alvar, Ball, & Burkett, 2002; Rhea, Ball, Phillips, & Burkett, 2002). In addition, because such changes are thought to be relatively specific to the training mode being utilized, it has been suggested that 1-RM testing should be used to establish baseline strength measures and changes in strength during traditional isoinertial weight training programs (Abernethy & Jurimae, 1996).

It has been demonstrated that the test-retest reliability of 1-RM measures is generally good for a variety of lower extremity exercises across a range of ages (see Table 2.3). For example, in the Phillips, Batterham, Valenzuela, & Burkett (2004) study it was reported that no systematic bias was evident for men across three 1-RM trials for the leg press exercise, while the mean random error actually decreased across consecutive pairs of trials (random error for all 3 trials taken as a unit was 4.3% of the mean). However, for the women in this study a small but statistically significant shift in the 1-RM mean of 3.6% occurred between trials 2 and 3, although no systematic bias was evident between trials 1 and 2. In addition, the random error for the women across consecutive pairs of trials was relatively stable at ≈5-6%.

Ploutz-Snyder & Giamis (2001) also demonstrated good 1-RM test-retest accuracy in their study with mean differences between trials of 0.7% for younger adults and 1.3% for older adults. However, it should be recognized that the younger subjects took an average of 3.6 sessions to reach this degree of accuracy, while the older subjects took an average of 8.8 sessions. Based on these results, the authors suggested that familiarization sessions are necessary to improve the reliability of 1-RM testing. In addition, a number of other authors have suggested that standardized testing protocols and at least one familiarization session are necessary for optimal 1-RM testing reliability (McCurdy, Langford, Cline, Doscher, & Hoff, 2004; Phillips et al., 2004; Ploutz-Snyder & Giamis, 2001; Salem, Wang, & Sigward, 2002). Importantly however, Salem, Wang and Sigward (2002) demonstrated that the reliability of 1-RM testing for leg press and knee extension exercises remained stable for three weeks following a single practice session.

Table 2.3: Reliability of 1-RM Measures

Study	Subjects	Exercise	Relevant Findings
Augustsson, Thomee, & Karlsson (2004)	ACL-R (mean time post-op 11 months; M=19)	Unilateral knee extension (min 7 days between tests)	Test-retest reliability for involved and uninvolved knees: ICC=0.96
Braith, Graves, Leggett, & Pollock (1993)	Healthy untrained (M=33; F=25)	Bilateral knee extension (minimum of 48 hrs between tests)	Test-retest reliability Pearson correlation coefficient: r=0.98 Percentage increase in the mean 1-RM between test 1 and test 2 = 4.4%
	Healthy post 18wks strength training (M=25; F=22)	Bilateral knee extension (minimum of 48 hrs between tests)	Test-retest reliability Pearson correlation coefficient: r=0.99 Percentage increase in the mean 1-RM between test 1 and test 2 = 2.8%
Cronin & Henderson (2004)	Healthy male novice weight trainers (n=10)	Unilateral supine squat (four testing sessions each 7-10 days apart)	Significant increase in mean 1-RM between tests 1 & 2 (9.8%), 1 & 3 (13.8%) and 1 & 4 (16.8%). No difference between tests 3 and 4 (α level = 0.05).
		Bilateral supine squat (four testing sessions each 7-10 days apart)	Significant increase in mean 1-RM between tests 1 & 2 (6.8%), 1 & 3 (9.9%) and 1 & 4 (15.0%). No difference between tests 3 and 4.
Faigenbaum et al (1998)	Healthy untrained children (10.4 ± 1.2 years; M=13; F=8)	Bilateral leg press	ICC=0.93 SD=9.8kg SEM=2.2kg
Hoeger, Hopkins, Barette, & Hale (1990)	Healthy male subjects (training status unknown; n=16)	Bilateral leg press (24 hrs between tests)	r=0.89
		Bilateral knee extension (24 hrs between tests)	r=0.98
	Healthy female subjects (training status unknown; n=12)	Bilateral leg press (24 hrs between tests)	r=0.88
		Bilateral knee extension (24 hrs between tests)	r=0.92

Table 2.3 Continued: Reliability of 1-RM Measures

Study	Subjects	Exercise	Relevant Findings
McCurdy, Langford, Cline, Doscher, & Hoff (2004)	Healthy untrained (M=8; F=22)	Modified unilateral squat (48 hrs between tests)	ICC: M=0.99 F=0.97 Mean differences between tests (±SD): M=2.84 kg (3.15) F=1.75 kg (2.64) SEM: M=1.11 kg F=0.56 kg
	Healthy trained (M=10; F=12)	Modified unilateral squat (48 hrs between tests)	ICC: M=0.98 F=0.99 Mean differences between tests (±SD): M=7.05 kg (3.78) F=1.14 kg (1.53) SEM: M=1.20 kg F=0.44 kg
	Randomly selected from both groups (n=20)	Modified unilateral squat (72 hrs after second test)	ICC (Test 3 vs 2)=1.00 Mean differences between tests (±SD): 0.80 kg (2.79) SEM=0.62 kg
Patterson, Sherman, Hitzelberger, & Nichols (1996)	Healthy trained (M=21; F=29)	Bilateral leg press (two testing sessions 3-7 days apart)	Test-retest reliability coefficients (determined using one-way ANOVA): M=0.69 F=0.91
	Healthy trained (M=13; F=29)	Bilateral leg extension (two testing sessions 3-7 days apart)	M=0.74 F=0.97

Table 2.3 Continued: Reliability of 1-RM Measures

Study	Subjects	Exercise	Relevant Findings
Phillips, Batterham, Valenzuela, & Burkett (2004)	Healthy untrained older (75.4 ± 4.7 years; M=16; F=31)	Bilateral leg press (three testing sessions conducted on non-consecutive days)	**Trial 2 versus Trial 1:** Percentage shift in 1-RM mean (95% CI): M= -0.4% (-5.1 to 4.6) F= -0.1% (-3.2 to 3.1) Percentage coefficient of variation (95% CI): M=6.7% (5.1 to 10.9) F=6.3% (5.1 to 8.7) **Trial 3 versus Trial 2:** Percentage shift in 1-RM mean (95% CI): M=2.0% (-0.5to 4.7) F= -3.6% (0.8 to 6.6) Percentage coefficient of variation (95% CI): M=3.4% (2.6 to 5.5) F=5.6% (4.6 to 7.8) **Familiarization and Testing Sessions:** 3 familiarization and 2-3 testing sessions produced highly reliable 1-RM measures
Ploutz-Snyder & Giamis (2001)	Healthy untrained younger females (23 ± 4 years; n=7) Healthy untrained older females (66 ± 5 years; n=6)	Bilateral leg extension (minimum of 48 hrs between tests)	**Mean (±SE) and range for the number of test sessions before consecutive 1-RM values were ± 1kg:** Younger females: Mean=3.6 (±0.6) sessions Range=2-5 sessions Older females: Mean=8.8 (±0.6) sessions Range=7-10 sessions **Test-Retest Reliability for the Final Two Testing Sessions:** r^2=0.94 No significant difference between the final 2 strength values ($p > 0.05$)

Table 2.3 Continued: Reliability of 1-RM Measures

Study	Subjects	Exercise	Relevant Findings
Salem, Wang, & Sigward (2002)	Healthy untrained older (65.2 ± 6.3 years; n=30)		Between-session reliability (Cranach's alpha)
		Bilateral leg press (testing 1 x week for 4 wks)	Test 1 to test 2: 0.979 Test 3 to test 4: 0.982 Test 1 to test 4: 0.986
		Bilateral leg extension (testing 1 x week for 4 wks)	Test 1 to test 2: 0.975 Test 3 to test 4: 0.975 Test 1 to test 4: 0.970

ACL-R = Anterior cruciate ligament reconstructed; ACL-D = Anterior cruciate ligament deficient; ICC = Intraclass correlation coefficient; SEM = Standard error of measurement, M = Male; F = Female.

While the 1-RM test appears to be a sensitive and reliable measure of maximal muscle strength, there are a number of factors related to the practical application of this technique that need to be considered. These include the time required for testing and issues related to lifting heavy loads such as apprehension, fear of failure and the risk of injury.

The 1-RM test can be time consuming because it typically involves a trial and error approach whereby weight is progressively added during an exercise until the point is reached where only one repetition of the movement can be performed with correct technique through the specified ROM (Brown & Weir, 2001; Pereira & Gomes, 2003). While the number of trials required before the actual 1-RM is reached is likely to vary between subjects, the results of a number of studies appear to suggest that a range of 3-6 trials is common (Mayhew, Ball, Arnold et al., 1992; McCurdy et al., 2004; Ploutz-Snyder & Giamis, 2001; Rhea, Alvar et al., 2002; Rhea, Ball et al., 2002; Salem et al., 2002; Woods, Bridge, Nelson, Risse, & Pincivero, 2004). In addition, it has been argued that rest periods are necessary between trials to allow for the recovery of anaerobic energy systems and specifically the replenishment of phosphocreatine stores (Matuszak, Fry, Weiss, Ireland, & McKnight, 2003; Ploutz-Snyder & Giamis, 2001; Weir, Wagner, & Housh, 1994). While two studies using trained subjects have demonstrated that rest periods of as little as one minute are adequate for recovery during 1-RM strength testing (Matuszak et al., 2003; Weir et al., 1994), many studies using 1-RM protocols have taken a slightly more conservative approach and utilized rest periods of 3-5 minutes (Adams, Swank, Barnard, Berning, & Sevene, 2000; Horvat et al., 2003; Kraemer et al., 2004; McCurdy et al., 2004; Taylor & Bandy, 2005; Wood, Maddalozzo, & Harter, 2002). Thus, when one considers that a minimum of one familiarization session is recommended before testing even begins, it becomes apparent that determining a 1-RM, even for a single exercise, could be a time consuming process for both the tester and the subjects. For example, Chapman, Whitehead, & Binkert (1998) reported that a 1-RM bench press test took 6 hours to complete using three examiners when testing 98 participants. In contrast, a sub-maximal 1-RM prediction test took just 2.5 hours to complete using only one examiner.

One repetition maximum testing has also been criticised because lifting heavy loads could potentially engender apprehension, fear of injury and/or fear of failure in some individuals and consequently lead to an underestimation of maximal muscle strength (Kim, Mayhew, & Peterson, 2002; Mayhew, Ball, Arnold et al., 1992; Mayhew, Ware, & Prinster, 1993). Certainly it is possible that such feelings might be particularly powerful in untrained individuals or those with injuries. In addition, a fear of exacerbating a client's injuries might lead some healthcare providers to abandon 1-RM testing in favour of techniques that are perceived as less hazardous. However, strength testing procedures such as MMT, isometric dynamometry and isokinetic dynamometry also require maximal force production and might therefore increase the risk of symptom exacerbation or re-injury. In any case, these issues again serve to highlight the potential utility of tests that use sub-maximal efforts to establish maximal strength values, such as 1-RM prediction equations.

Finally, a number of authors have expressed concerns about the risk of injury associated with 1-RM testing in various populations including older adults, children, adolescents, cardiac patients, pulmonary patients, novice weight lifters and injured subjects (Abadie, Altorfer, & Schuler, 1999; Barnard, Adams, Swank, Mann, & Denny, 1999; Braith et al., 1993; Brzycki, 1993; Cummings & Finn, 1998; Di Fabio, 2001; Grimsby, 2001; Kaelin et al., 1999; Kravitz et al., 2003; Mayhew, Ball, Arnold et al., 1992; Mayhew, Ware et al., 1993). However, despite the perception that 1-RM testing might be hazardous in some populations, reports of injuries directly associated with 1-RM testing appear to be relatively sparse. Only three studies describing injuries related to 1-RM testing were found and all of these studies involved older adults. Pollock, Carroll, Graves, Leggett, Braith, Limacher, & Hagberg (1991) reported that 1-RM testing resulted in 11 injuries in a group of 57 subjects (age range 70-79), while Shaw, McCully, & Posner (1995) reported two injuries among a group of 83 subjects (average age 65.8 ± 6.2 years) during 1-RM testing for five different exercises. In addition, Salem, Wang, & Sigward (2002) reported one injury (exacerbation of a previous back injury) among a group of 32 subjects (age range 51-78 years) during four different lower extremity 1-RM tests. In contrast, a number of studies have specifically investigated the safety of 1-RM testing in older adults, children, cardiac patients, pulmonary patients and healthy populations and have failed to report any adverse reactions to this procedure (Adams et al., 2000; Barnard et al., 1999; Faigenbaum, Milliken, & Westcott, 2003; Faigenbaum, Skrinar, Cesare, Kraemer, & Thomas, 1990; Gordon et al., 1995; Kaelin et al., 1999; Werber-Zion, Goldhammer, Shaar, & Pollock, 2004). In addition, numerous studies have used 1-RM testing to establish baseline measures, loading strategies and outcome measures for a variety of interventions across a range of populations including healthy subjects, neurologically impaired subjects and ACL injured subjects, apparently without incident (Augustsson et al., 2004; Augustsson et al., 2006; Faigenbaum et al., 2002; Faigenbaum et al., 1998; Holviala, Sallinen, Kraemer, Alen, & Hakkinen, 2006; Kalapotharakos, Michalopoulos, Tokmakidis, Godolias, & Gourgoulis, 2005; Kalapotharakos, Tokmakidis et al., 2005; Neeter et al., 2006; Osternig, Ferber, Mercer, & Davis, 2000; Ryushi et al., 2000; Taylor, Dodd, & Damiano, 2005; Tollbaeck et al., 1999). Nevertheless, it is logical, particularly in subjects with injuries or joint pathologies, that any assessment of strength should minimize the potential for tissue damage. Consequently, a number of 1-RM prediction equations have been developed to determine maximal muscle strength from the number of repetitions to failure performed at sub-maximal loads. These prediction equations will be discussed in more detail in the following section.

2.6. ONE REPETITION MAXIMUM PREDICTION EQUATIONS

One repetition maximum prediction equations are based on the relationship between maximal muscle strength and the number of repetitions to failure (RTFs) that can be performed at selected percentages of 1-RM. While many 1-RM prediction equations exist, some have been categorised as exercise or population specific and are therefore unlikely to be useful in general clinical practice (Abadie & Wentworth, 2000; Akinpelu, Iyaniwura, & Ajagbe, 2001; Reynolds, Gordon, & Robergs, 2006; Ware, Clemens, Mayhew, & Johnston, 1995; Whisenant, Panton, East, & Broeder, 2003). As a consequence, eleven generic 1-RM prediction equations were selected for this literature review (Table 2.4). Importantly, while the differences in 1-RM percentages between these equations are often small, they can be considerable in some instances, particularly when RTFs are > 10 (see Table 2.5). Therefore, the accuracy of these equations will differ under some conditions. In addition, it should be recognized that the origins of these equations are varied. In an early study, Berger (1961) used 94 male subjects to determine the mean percentage of 1-RM lifted for the bench press exercise while performing 5 RTFs and 10 RTFs. The author reported that the mean percentage of 1-RM lifted for 5 RTFS was 89.8%, while the mean percentage of 1-RM lifted for 10 RTFs was 78.9%. The author also reported correlation coefficients of 0.968 between the 1-RM and 5 RTF values and 0.953 between the 1-RM and 10 RTF values. Based on these results, Berger suggested that 1-RM performance could be calculated from the 5 and 10 RTF values. This data was then used to extrapolate the percentages of 1-RM for all other RTFs < 10 and converted into a table that could be used to predict 1-RM performance from RTFs. Because of the potential advantages of estimating maximal muscle strength from sub-maximal loads, a number of other authors have subsequently developed similar tables. It is from tables such as these that many 1-RM prediction equations have been retrospectively derived. However, it appears that rigorous quantitative research methods have rarely been employed when collecting the data used to construct these tables. For example, Wood, Maddalozzo, & Harter (2002) reported that the Lander equation "began as a 'guess-timated' chart that was eventually published without the author's knowledge". Other equations including the Epley, O'Connor and Wathen equations also appear to have been derived from tables with equally ambiguous origins (Wood et al., 2002). Similarly, the Adams equation was apparently based on a number of sources including the works of Hoeger, Barette, Hale, & Hopkins (1987) and Lander (1984). In addition, the Brzycki equation was derived from a graph created by Sale & MacDougall (1981) which was based on

Table 2.4: 1-RM Prediction Equations

Prediction Equation	Formula
Adams[1]	1-RMP = W/(1-0.02*R)
Berger[1]	1-RMP = W/(1.0261 $e^{-0.0262*R}$)
Brown[1]	1-RMP = (R*0.0328 + 0.9849)*W
Brzycki[1]	1-RMP = W/(1.0278-0.0278*R)
Epley or Welday[1]	1-RMP = (0.033*R*W)+W
KLW[2]	1-RMP = W*(0.988–0.0000584*R^3+0.00190*R^2+0.0104*R)
Lander[1]	1-RMP = W/(1.013-0.0267123*R)
Lombardi[1]	1-RMP = $R^{0.1}$*W
Mayhew et al.[1]	1-RMP = W/(0.522+0.419$e^{-0.055*R}$)
O'Connor et al.[1]	1-RMP = 0.025 (W*R)+W
Wathen[1]	1-RMP = W/(0.488+0.538$e^{-0.075*R}$)

1-RMP = predicted 1-RM; R = repetitions to failure; W = weight used for repetitions to failure.

[1]From Mayhew, Kerksick, Lentz, Ware, & Mayhew (2004)

[2] Kemmler, Lauber, Wassermann, & Mayhew (2006)

the unpublished observations of Anderson & Haring (1977). Indeed, other than the Berger equation, it seems that only the Mayhew et al. and KLW equations were developed from data which was collected using quantitative research methods and subsequently published in research journals. Importantly, the authors of the Mayhew et al. equation also made efforts to cross-validate the accuracy of their equation in a variety of populations. In contrast, it appears that only retrospective efforts have been made to rigorously investigate the accuracy of the other prediction equations. Nevertheless, the existing literature relating to the accuracy of 1-RM prediction equations will be reviewed in the following sub-sections. Emphasis will be placed on

Table 2.5: Repetitions to Failure and their Respective Estimated Percentages of 1-RM for Different Prediction Equations

Reps	1-RM Prediction Equations (Estimated % of 1-RM)											
	Adams	Berger[1]	Brzycki	Brown	Epley	Lander	KLW	Lombardi	Mayhew[2]	O'Conner	Poliquin	Wathen
1	98	100.0	100	98.2	96.8	98.6	100.0	100	91.9	97.6	100	98.7
2	96	97.4	97.2	95.2	93.8	96.0	98.4	93.3	89.7	95.2	94.3	95.1
3	94	94.9	94.4	92.3	91.0	93.3	96.6	89.6	87.7	93.0	90.6	91.8
4	92	92.4	91.7	89.6	88.3	90.6	94.7	87.1	85.8	90.9	88.1	88.7
5	90	90.0	88.9	87.0	85.8	87.9	92.6	85.1	84.0	88.9	85.6	85.8
6	88	87.7	86.1	84.6	83.5	85.3	90.4	83.6	82.3	87.0	83.1	83.1
7	86	85.4	83.3	82.3	81.2	82.6	88.2	82.3	80.7	85.1	80.7	80.6
8	84	83.2	80.5	80.2	79.1	79.9	86.0	81.2	79.2	83.3	78.6	78.3
9	82	81.1	77.8	78.1	77.1	77.3	83.8	80.3	77.7	81.6	76.5	76.2
10	80	79.0	75	76.2	75.2	74.6	81.7	79.4	76.4	80.0	74.4	74.2
11	78	76.9	72.2	74.3	73.4	71.9	79.7	78.7	75.1	78.4	-	72.4
12	76	74.9	69.4	72.5	71.6	69.2	77.8	78.0	73.9	76.9	-	70.7
13	74	73.0	66.6	70.9	70.0	66.6	76.0	77.4	72.7	75.5	-	69.1
14	72	71.1	63.9	69.2	68.4	63.9	74.3	76.8	71.6	74.1	-	67.6
15	70	69.3	61.1	67.7	66.9	61.2	72.8	76.3	70.6	72.7	-	66.3
16	68	67.5	58.3	66.2	65.4	58.6	71.3	75.8	69.6	71.4	-	65.0
17	66	65.7	55.5	64.8	64.1	55.9	70.1	75.3	68.6	70.2	-	63.8
18	64	64.0	52.7	63.5	62.7	53.2	69.0	74.9	67.8	69.0	-	62.7
19	62	62.4	50	62.2	61.5	50.5	68.0	74.5	66.9	67.8	-	61.7
20	60	60.8	47.2	60.9	60.2	47.9	67.2	74.1	66.1	66.7	-	60.8

Modified from Chapman, Whitehead, & Binkert (1998). [1] Some percentages calculated from the derived Berger equation differ slightly from those reported in the original Berger (1961) table. [2] Some percentages calculated for the Mayhew et al. equation differ from those reported by Chapman et al. (1998) – the reason for this is unclear.

examining the variables that might influence the accuracy of 1-RM prediction equations including the load lifted, the number of RTFs performed, the speed at which RTFs are performed, the equipment and exercises being utilized and the training status, gender, age and anthropometric characteristics of the subjects being investigated. Because some of the studies being reviewed have addressed more than one of these variables, they may appear in multiple sub-sections. However, only the relevant variable will be discussed in each section. Finally, it should be recognized that many studies have reported high correlation coefficients as evidence of the conformity between predicted and actual 1-RM performance. However, as Bland and Altman (1986) stated, a correlation coefficient "measures the strength of a relation between two variables, not the agreement between them". Therefore, while correlation coefficients may indicate the degree to which predicted 1-RM performance increases as actual 1-RM performance increases, they do not provide evidence about the level of agreement between predicted and actual 1-RM performance. For this reason, reports of similarity statistics and error measurements have also been included when available.

2.6.1. Load and Repetitions to Failure

When considering the influence of load and RTFs on the accuracy of 1-RM prediction equations, there appear to be three main issues that need to be addressed. The first involves the general question of whether estimating 1-RM performance is more accurate when using heavier loads that generate less RTFs or when using lighter loads that generate more RTFs. The second issue relates to the question of whether certain generic 1-RM prediction equations are more accurate with loads that generate RTFs $\leq$ 10. The third and final issue relates to how heavier or lighter loads might influence the number of RTFs that can be completed when performing different exercises.

2.6.1.1. Predicting 1-RM Performance with High and Low RTFs

Some studies have provided evidence which suggests that the prediction of 1-RM performance can be accurate with low loads that generate high numbers of RTFs. Invergo, Ball, & Looney (1991) used 144 males to compare the accuracy of push-ups to the Young Men's Christian Association (YMCA) bench press test when predicting

1-RM bench press performance. Additionally, a prediction equation derived from this population was cross-validated in a group of 48 males. The YMCA test involved lifting a 36.4 kg load to failure at a cadence of 60 repetitions per second. The authors reported that the first group performed an average of 29.2 (± 10.5) repetitions for the YMCA test and 34.7 (± 11.7) repetitions for the push-ups. Using regression analysis the authors found that the YMCA test was more accurate for predicting 1-RM performance (accounted for 86% of the variance; standard error of the estimate [SEE] = 6.03 kg) than push-ups (accounted for 31% of the variance; SEE = 13.33 kg). When the authors cross-validated the prediction equation developed from the YMCA test results they found it accounted for 91% of the variance between predicted and actual 1-RM bench press performance (SEE = 4.49 kg). Based on these results, the authors suggested that an absolute endurance test using 36.3 kg could be used to accurately assess 1-RM bench press performance in untrained and moderately trained males. However, the authors conceded that the use of a relatively light fixed load might make this test inappropriate for individuals who exhibit high levels of 1-RM strength.

Rose & Ball (1992) also investigated the accuracy of the YMCA bench press test when estimating 1-RM performance, this time in a group of 64 untrained women. The YMCA test normally involves a load of 15.9 kg for women but in this study the authors also investigated a modified load of 20.4 kg. The authors reported that, on average, 30.0 (± 9.5) repetitions and 17.6 (± 7.3) repetitions were performed with the 15.9 kg and 20.4 kg loads, respectively. Using a multiple regression analysis, the authors found that the 20.4 kg load was more accurate for estimating 1-RM performance (accounted for 67% of variance; SEE = 3.14 kg) than the 15.9 kg load (accounted for 62% of variance; SEE = 3.34 kg). Based on these results, the authors suggested that an absolute endurance test was accurate when predicting 1-RM bench press performance in untrained women. However, they also conceded that the use of relatively light fixed loads might not be appropriate for well trained females.

Kim, Mayhew, & Peterson (2002) also investigated the accuracy of the YMCA bench press test when estimating 1-RM performance, this time in a group of untrained college students (37 males, 21 females). Using a 15.9 kg load for females and a 36.4 kg load for males, the subjects performed two tests of RTFs at cadences of 30 and 60 repetitions per minute. At 30 and 60 repetitions per second, the females performed

41.3 (± 17.2) RTFs and 32.0 (± 18.2) RTFs, respectively, while the males performed 33.0 (± 13.7) RTFs and 35.8 (± 17.0) RTFs, respectively. The authors found that RTFs at either cadence were good predictors of 1-RM bench press performance in both genders (men: 30 reps·per minute, $r^2 = 0.757$, SEE = 8.0 kg; 60 reps per·minute, $r^2 = 0.884$, SEE = 8.2 kg; women: 30 reps·per minute, $r^2 = 0.754$, SEE = 3.1 kg; 60 reps·per minute, $r^2 = 0.816$, SEE = 2.7 kg). Based on these results, the authors suggested that when using both fast and slow cadences, the YMCA bench press test can provide a valid estimation of 1-RM performance in untrained young men and women. However, they also conceded that the use of relatively light fixed loads might diminish the accuracy of the YMCA tests when estimating 1-RM performance in strength-trained individuals.

In a more recent study, Horvat et al. (2003) investigated the accuracy of using 25 kg and 31.8 kg loads when predicting 1-RM bench press performance in 65 female college athletes. The authors reported that the mean number of RTFs performed with the 25 kg and 31.8 kg loads were 26.78 and 15.31 repetitions, respectively. The authors also analysed a number of variables to determine which were useful in predicting 1-RM performance. The authors found that RTFs at 31.8 kg, RTFs at 25 kg, and lean body mass (LBM) had p values of < 0.05, which indicated that each of these variables made significant unique contributions to the prediction of 1-RM performance. Using these variables, the authors developed different 1-RM prediction equations and found that an equation consisting of LBM and RTFs at 31.8 kg was a better predictor of 1-RM performance ($R^2 = 0.832$) than an equation consisting of LBM and RTFs at 25 kg ($R^2 = 0.787$). In addition, the authors reported a greater correlation between actual and predicted 1-RM values when using the RTFs at 31.8 kg / LBM regression equation (r = 0.916) compared to the RTFs at 25 kg / LBM regression equation (r = 0.891). Based on these findings, the authors selected the 31.8 kg load as the best predictor of 1-RM performance.

Although the four studies discussed above have demonstrated that lighter loads and high RTFs can be used to predict 1-RM performance with some accuracy, they did not specifically investigate whether much heavier loads might have resulted in an even greater degree of predictive accuracy. However, a study by Mayhew, Ball, Arnold, & Bowen (1992) did address this issue. The authors used a sample of college students consisting of 184 males and 251 females who were tested after completing a 14 week fitness course. Using the bench press exercise, each subject was randomly assigned a load corresponding to 55-95% of their 1-RM and asked to perform as many repetitions as possible in one minute. From this data the authors developed the Mayhew et al. 1-RM prediction equation. Importantly, as part of their investigation the authors separated the sample into different groups based upon the number of RTFs performed and the percentage of 1-RM load that was used (see Table 2.6). The authors reported that the correlations between predicted and actual 1-RM were above r = 0.87 with comparably low SEEs for all of the groups. Based on these results, the authors argued that higher RTFs with lighter loads appeared to be as effective as lower RTFs with heavier loads when estimating 1-RM bench press performance.

Table 2.6: Accuracy of prediction at different RTFs and percentages of 1-RM

	Males			**Females**		
	n	**r^1**	**SEE (kg)**	**n**	**r^1**	**SEE (kg)**
Repetitions						
2-5	47	0.95	5.2	38	0.92	3.1
6-10	41	0.93	6.7	55	0.93	3.3
11-15	51	0.96	5.9	56	0.88	4.0
> 15	45	0.98	4.8	102	0.87	2.9
Percentage of 1-RM						
55-59	6	0.99	4.2	15	0.95	2.2
60-69	56	0.98	4.9	89	0.87	3.7
70-79	51	0.97	4.9	70	0.94	3.0
80-89	42	0.98	3.5	53	0.93	3.1
90-95	29	0.97	4.3	24	0.96	2.6

[1]All correlations significant at $p < 0.01$
SEE = Standard error of estimate, n = number of subjects
Modified from Mayhew, Ball, Arnold, & Bowen (1992)

In a more recent study, Kravitz, Akalan, Nowicki, & Kinzey (2003) also used different percentages of 1-RM (70%, 80% and 90%) to develop prediction equations for the bench press, squat and deadlift exercises. Using 18 adolescent male power-lifters, the authors found that loads of 70% of 1-RM yielded the best prediction equations for the bench press and squat with SEEs of 2.69 kg and 5.06 kg, respectively. At 70% of 1-RM, the mean number of RTFs for the bench press and squat were 16 (± 2.38) and 13 (± 3.18) repetitions, respectively. For the deadlift, the 80% of 1-RM load yielded the best prediction equation with an SEE of 4.97 kg. At 80% of 1-RM, the mean number of RTFs for the deadlift was 12 (± 3.17) repetitions. Based on these findings, the authors suggested that 1-RM bench press and squat performance was predicted with an acceptable degree of accuracy using loads of 70% of 1-RM and RTF ranges of 14-18 and 10-16 repetitions, respectively. In addition, the authors suggested that an acceptable degree of predictive accuracy was attained for the deadlift using an 80% of 1-RM load with a RTF range of 9-14 repetitions.

In contrast to the studies described above, a number of other investigations have suggested that higher loads and lower RTFs may provide more accurate estimates of 1-RM performance. For example, Chapman, Whitehead, & Binkert (1998) investigated the accuracy of the National Football League (NFL) 225 lb (102.1 kg) RTF test when used to predict bench press 1-RM performance in 98 college football players. The authors reported that the mean number of RTFs performed with this load was 7.2 (± 5.5) repetitions. In addition, the NFL test was found to be highly correlated with actual 1-RM performance ($r = 0.96$, $p < 0.001$), with a relatively low SEE of 4.9 kg (4%). Finally, a separate analysis of subjects who performed > 10 RTFs and subjects who performed ≤ 10 RTFs demonstrated that predictive accuracy was greater in the latter group ($R^2 = 0.85$ vs. $R^2 = 0.76$), although SEE values were not provided for these groups.

In another study that examined the NFL bench press test, Mayhew, Ware, Bemben, Wilt, Ward, Farris, Juraszek, & Slovak (1999) used 114 college football players to develop a 1-RM prediction equation, which was then cross validated in another sample of 28 players. The prediction equation had a reported SEE of 6.4 kg (4.7%) for the original group. However, the error was smaller for players who performed < 10 repetitions (SEE = 5.2 kg, 3.8%) compared to players who performed > 10 repetitions (SEE = 7.8 kg, 5.7%). In addition, the players who performed ≤ 10 RTFs used an average load of 84.4% of 1-RM, whereas the players who performed > 10 RTFs used an average load of 66.4% of 1 RM. Importantly, an analysis of the cross-validation group demonstrated that when players completed ≤ 10 repetitions ($n = 19$), the difference between predicted and actual 1 RM produced an average underestimation of 0.18 kg (0.1%), with a 95% confidence interval on the average difference that ranged from 2.9 kg (2.1%) below to 2.5 kg (1.8%) above actual 1 RM values. In contrast, the authors found that when players completed > 10 repetitions (n = 9), the difference between predicted and actual 1 RM produced an average overestimation of 1.9 kg, with a 95% confidence interval on the average difference that ranged from 2.8 kg (2.0%) below and 6.6 kg (4.8%) above actual 1 RM values. Based on these findings, the authors suggested that RTFs with an absolute load of 102.1 kg accurately predicted 1-RM bench press performance in college football players, although the prediction error increased when RTFs exceeded 10 repetitions.

Mayhew, Ware, Cannon, Corbett, Chapman, Bemben, Ward, Farris, Juraszek, & Slovak (2002) also used the NFL bench press test to develop a 1-RM prediction equation from a group of 260 college football players. The authors found that the resultant equation was significantly correlated to 1-RM performance (r = 0.94) and yielded a SEE of 8.3 kg. However, they also found that the accuracy of the equation decreased as RTFs increased. When subjects performed ≤ 10 RTFs the SEE was 6.5 kg. In contrast, the SEE increased to 8.4 kg when subjects performed 11 to 20 RTFs and to 13.8 kg when subjects performed > 20 RTFs. Based on these findings, the authors suggested that 1-RM prediction accuracy decreased as RTFs increased.

In a more recent study, Reynolds, Gordon, & Robergs (2006) used 70 subjects (34 males, 36 females: 18–69 years of age), to investigate the decrease in the load lifted when performing one, five, 10, and 20 RTFs for the free-weight bench press and machine-weight leg press exercises. In addition, the authors developed prediction equations for 1-RM performance from the multiple RTF tests. The authors reported that the mean percentages of 1-RM were 87.45%, 75.65% and 61.61% for the bench press and 85.91%, 70.10% and 51.58% for the leg press, at 5, 10 and 20 repetitions respectively. In addition, the authors found that the mean data for the bench press and leg press were best fit by a nonlinear model (SEEs = 0.2 kg and 2.4 kg, respectively) rather than a linear model (SEEs = 2.6 kg and 11.2 kg). When the authors developed prediction equations from the bench press and leg press data, they found that the 5 RTF equations produced considerably lower error (bench press SEE = 2.98 kg, leg press SEE = 16.16 kg) than the 10 RTF (bench press SEE = 5.38 kg, leg press SEE =

26.13 kg) or 20 RTF (bench press SEE = 7.36 kg, leg press SEE = 29.41 kg) equations. The equations were then cross-validated in a group of 20 subjects and the authors reported a similar pattern for the 5 RTF (bench press SEE = 1.80 kg, leg press SEE = 13.51 kg), 10 RTF (bench press SEE = 3.64 kg, leg press SEE = 23.79 kg) and 20 RTF (bench press SEE = 4.82 kg, leg press SEE = 33.08 kg) equations. Based on these findings, the authors argued that the most accurate RTF range when predicting 1-RM bench press and leg press performance was 5 RTFs.

In conclusion, it appears that a number of different techniques can be employed to accurately estimate 1-RM performance using both lighter loads (high RTFs) and heavier loads (low RTFs). However, a number of studies have suggested that the accuracy of specific generic 1-RM prediction equations may vary when lighter or heavier loads are utilized. These studies will be discussed in the following section.

2.6.1.2. Accuracy of Prediction Equations with High and Low RTFs

The one repetition maximum prediction equations being investigated in this thesis are based on the relationship between maximal muscle strength and the number of RTFs that can be performed at selected percentages of 1-RM. Numerous studies have demonstrated that as the load increases, the number of RTFs performed decreases (Hoeger et al., 1987; Reynolds et al., 2006; Sale & MacDougall, 1981). In addition, it has been proposed that loads which result in RTFs ≤ 10 are more likely to test maximal muscle strength, whereas loads which result in RTFs > 10 are more likely to challenge local muscular endurance (Hoeger et al., 1987; Hoeger et al., 1990). It has also been suggested that the relationship between load and RTFs is near linear when the number of RTFs are ≤ 10, but becomes curvilinear when RTFs are > 10 (Brzycki, 1993; Mayhew, Ball, Arnold et al., 1992; Reynolds et al., 2006; Sale & MacDougall, 1981). This is particularly important because some 1-RM prediction equations were developed as curvilinear equations (Berger, KLW, Lombardi, Mayhew et al and Wathen equations), while others were developed as linear equations (Adams, Brown, Brzycki, Epley, Lander and O'Connor equations). As a consequence it would seem likely that linear equations might be more accurate when RTFs are ≤ 10, while curvilinear equations might be accurate over a greater range of RTFs. Indeed, some authors have suggested RTF ranges for their equations. Brzycki (1993) and apparently

Epley (cited in Reynolds et al., 2006) stated RTFs < 10 should be used with their equations, while Berger (1961) and apparently Lombardi (cited in Reynolds et al., 2006) suggested RTFs < 11 should be used with their equations. In contrast, Mayhew, Ball, Arnold, & Bowen (1992) suggested that RTFs < 15 could be used with their equation, while Kemmler, Lauber, Wassermann, & Mayhew (2006) suggested that RTFs < 20 could be used with their equation.

Importantly, a number of studies have investigated the effects of different loads and RTF numbers on the accuracy of specific 1-RM prediction equations. Arnold, Mayhew, LeSeur, & McCormick (1995) used 47 college students to investigate the accuracy of six 1-RM prediction equations when using lighter (65 % of 1-RM) and heavier (85% of 1-RM) loads for the bench press and squat exercises. At 65% of 1-RM, four of the equations significantly overestimated bench press 1-RM performance by an average of 15.4%, while the other two equations significantly underestimated 1-RM performance by an average of 6.4%. For the squat exercise, three equations significantly underestimated 1-RM performance by 11.1%, two non-significantly underestimated by 1.3% and one non-significantly underestimated by 5.1%. In contrast, with the 85% of 1-RM load, five equations significantly overestimated bench press performance by an average of 5%, although the results for the other equation were not reported. For the squat exercise, five equations significantly overestimated 1-RM performance by an average of 3.6% and one equation non-significantly underestimated by 0.2%. Based on these findings, the authors suggested that the 85% of 1-RM load generally produced smaller percent differences from actual 1-RM values than the 65% of 1-RM load.

In another study, Ware, Clemens, Mayhew, & Johnston (1995) used 45 college football players to evaluate the accuracy of four prediction equations when used to estimate 1-RM bench press and squat performance. The subjects self-selected loads that averaged 71.3% (± 4.9) and 68.0% (± 4.5) of 1-RM and performed RTFs that averaged 13.9 and 17.4 repetitions for the bench press and squat exercises, respectively. The authors found that the Mayhew et al. equation significantly underestimated 1-RM bench press performance by an average of 3.1 kg (± 7.7 kg), while the Epley, Lander and Brzycki equations significantly overestimated 1-RM bench press performance by averages of 4.8 kg (± 8.2 kg), 14.1 kg (± 12.0 kg) and

14.2 kg (± 12.4 kg), respectively. For the squat, the authors found that the Mayhew et al., Epley, Lander and Brzycki equations all significantly overestimated 1-RM performance by averages of 48.5 kg (± 14.4 kg), 11.6 kg (± 11.5 kg), 45.7 (± 31.2 kg) and 47.9 kg (± 33.6 kg) respectively. In addition, the SEE and total error of the equations were significantly higher for the squat when compared to the bench press (SEE: bench press 5.8%- 6.7%, squat 4.9%-11.7%; Total Error: bench press 6.6%-13.6%, squat 8.6%-25.6%). Based on these results, the authors argued that only the Mayhew et al. equation was appropriate for estimating 1-RM bench press performance, while none of the equations were appropriate for estimating squat performance. However, the authors acknowledged that the prediction equations used in this study may have produced more accurate results if heavier loads (resulting in RTFs ≤ 10) had been utilized. In any case, the results appear to support the contention that RTFs > 10 may not be appropriate for linear equations, although it is unclear why the curvilinear Mayhew et al. equation was inaccurate for the squat. However, it is possible that the number of RTFs performed at the same percentage of 1-RM might differ for the bench press and squat exercises and therefore alter the accuracy of 1-RM prediction equations (see Exercise Type and Equipment section below).

In another study that examined load and RTFs, Mayhew, Prinster, Ware, Zimmer, Arabas, & Bemben (1995) investigated the accuracy of six prediction equations when used to estimate 1-RM bench press performance. For the total sample (n = 220), the Mayhew et al., O'Connor and Lombardi equations significantly underestimated 1-RM performance by averages of 1.7 kg, 4.8 kg and 7.8 kg, respectively, while the Epley, Lander and Brzycki equations significantly overestimated by averages of 2.7 kg, 13.7 kg and 14.2 kg, respectively. As part of their analysis, the authors divided the total sample into subjects who performed > 10 RTFs and subjects who performed ≤ 10 RTFs (see Table 2.7). The authors reported that the SEEs, total errors, correlations and average differences between actual and predicted 1-RM were considerably better for the subjects who performed ≤ 10 RTFs than for the subjects who performed > 10 RTFs. Based on these findings, the authors suggested that RTFs ≤ 10 were more effective than RTFs > 10 when predicting 1-RM bench press performance.

Table 2.7: Comparison between Predicted and Actual 1-RM Performance Using Various RTFs

Equations	Actual and Predicted 1-RM Values (kg) (mean ± SD)	SEE (kg)	Total Error (kg)	Mean Under- or Over-Estimation (kg)	r[1]
≤ 10 RTFs (n = 73)					
Actual 1-RM	86.9 ± 21.8				
Brzycki	87.4 ± 22.9	4.5	4.8	0.5	0.98
Lander	88.0 ± 23.0	4.5	4.8	1.1	0.98
Mayhew et al	88.2 ± 22.5	4.1	4.3	1.3	0.98
Epley	88.5 ± 22.9	4.1	4.6	1.6	0.98
Lombardi	85.5 ± 21.4	4.1	4.3	-1.4	0.98
O'Conner	83.9 ± 21.4	4.0	4.9	-3.0	0.98
> 10 RTFs (n = 147)					
Actual 1-RM	101.9 ± 26.6				
Brzycki	122.9 ± 40.7	16.7	33.3	21.0	0.78
Lander	121.7 ± 38.7	15.6	30.4	19.8	0.81
Mayhew et al	98.7 ± 26.5	7.6	8.3	-3.2	0.96
Epley	105.2 ± 28.0	6.5	7.6	3.3	0.97
Lombardi	90.9 ± 25.0	9.2	14.2	-11.0	0.94
O'Connor	96.2 ± 25.7	6.8	8.8	-5.7	0.97

[1] All correlations between predicted and actual bench press significant at $p < 0.01$

Modified from Mayhew et al (1995)

Wood, Maddalozzo, & Harter (2002) also investigated the effect of load and RTFs on the accuracy of seven prediction equations when estimating 1-RM performance for ten machine-weight exercises. The RTFs for each exercise were determined by assigning 49 older adults (53.55 ± 3.34 years) a percentage of their 1-RM, ranging from 50% to 90%. This methodology resulted in some subjects performing RTFs > 10. The results were analysed separately for the entire sample and for those subjects who performed RTFs ≤ 10. The authors found that the average error between predicted and actual 1-RM values (expressed as a percentage of 1-RM) was high for all of the prediction equations, across all of the exercises, for the entire sample (range of 12-157%). However, the average error was significantly less (range of 7-20%) for the subjects who performed RTF ≤ 10. Based on their findings, the authors stated that the relative accuracy, similarity, and average error of 1-RM prediction equations improved significantly when RTFs were ≤ 10.

In another study, Whisenant, Panton, East, & Broeder (2003) investigated the accuracy of seven generic prediction equations, one combination prediction equation and three NFL-225 specific prediction equations when using the NFL-225 lb test to predict bench press 1-RM performance in 69 college football players. The RTFs performed with this load averaged 12 (± 6) repetitions, with a range of 1-27 repetitions. Based on the reported average over- or underestimation of actual 1-RM performance for the entire sample, the percentage errors for the generic equations can be calculated as 1.0% (Epley), 1.3% (Wathen), 2.3% (Mayhew et al.), 5.5% (O'Connor), 8.1% (Lombardi), 10.4% (Lander), and 10.7% (Brzycki). In a subgroup of 31 subjects who performed RTFs ≤ 10, the percentage errors between mean predicted and actual 1-RM performance can be calculated as 0.7% (Epley), 0.7% (Lander), 1.1% (Lombardi), 1.1% (Wathen), 1.9% (Brzycki), 1.9% (Mayhew et al.) and 3.7% (O'Connor). In another subgroup of 33 subjects who performed 11-20 RTFs, the percentage errors between mean predicted and actual 1-RM performance can be calculated as 0.6 % (Epley), 1.2% (Wathen), 4.8% (Mayhew et al.), 7.5% (O'Connor), 11.7% (Lander), 11.7% (Lombardi), and 12% (Brzycki). Based on these calculations, it appears that there were considerable increases in error percentages for the Brzycki, Lander, Lombardi, Mayhew et al. and O'Connor equations but not for the Epley and Wathen equations, when RTFs were > 10.

Mayhew, Jacques, Ware, Chapman, Bemben, Ward, & Slovak (2004) also used the NFL-225 lb test to investigate the accuracy of four generic prediction equations and six NFL-225 specific prediction equations when estimating 1-RM bench press performance in 61 college football players. The RTFs performed with this load averaged 11.7 (± 5.5) repetitions, with a range of 1-27 repetitions. The authors reported that of the generic equations, only the Mayhew et al. equation produced predicted values that were not significantly different from actual 1RM performance. In addition, it was the only generic equation that predicted values within ± 4.5 kg of actual 1RM performance in more than 50% of the subjects. Importantly, when the authors analysed both the generic and specific prediction equations they found that prediction error was greater with RTFs ≥ 10 (± 6.5 kg) than with RTFs ≤10 (± 4.0 kg).

More recently, Kemmler, Lauber, Wassermann, & Mayhew (2006) used 70 females (age: 57.4 ± 3.1 years) to investigate the accuracy of eight prediction equations when estimating 1-RM performance for four machine-weight exercises. Repetitions to failure were performed for leg press, bench press, rowing, and leg adduction exercises in the following ranges: 3–5 RTFs, 6–10 RTFs, 11–15 RTFs, and 16–20 RTFs. The authors reported that an equation they developed (KLW equation) accurately predicted 1-RM performance for the four exercises with mean absolute differences between actual and predicted 1-RM performance of 1.5–3.1% and with coefficients of variation of ≤ 3.3%. Based on these results, the authors suggested that the accuracy of the equation was independent of exercise type or RTF numbers. However, the authors also reported that out of seven generic equations, only the O'Connor equation produced comparable results with mean absolute differences between actual and predicted 1-RM performance of 1.6–3.5% (except for the 3-6 RTF leg press = 6.2%). In contrast, the accuracy of the Brzycki, Epley, Lander, Lombardi, Mayhew et al. and Wathen equations varied considerably across the RTF ranges (range of mean absolute differences between actual and predicted 1RM performance: 1.8–32.1%). In addition, while the KLW and O'Connor equations were accurate over a wide range of RTFs, it appears that the predictive accuracy of the other equations was generally superior for the 3-5 and 6-10 RTF ranges compared to the 11-15 and 16-20 RTF ranges.

In conclusion, it appears that many of the 1-RM prediction equations being investigated in this thesis were designed to be used with loads that produce RTFs ≤ 10. In addition, the results of numerous studies have indicated that the predictive accuracy of these equations increases when RTFs are ≤ 10.

2.6.1.3. The Effect of Load on RTFs Performed for Different Exercises

The 1-RM prediction equations being investigated in this thesis are based on the relationship between maximal muscle strength and the number of RTFs that can be performed at selected percentages of 1-RM. Importantly, some studies have suggested that the number of RTFs completed at the same percentage of 1-RM may vary depending on the exercise being performed (see Exercise Type and Equipment section below). In addition, these studies have provided evidence that the difference in RTFs between exercises may be more pronounced when using lighter loads. This is important because such variations could have an impact on the accuracy of 1-RM prediction equations. In two studies which examined these issues, Hoeger, Barette, Hale, & Hopkins (1987) and Hoeger, Hopkins, Barette, & Hale (1990) used a total of 91 trained and untrained subjects to determine the number of RTFs that could be performed at 40%, 60% and 80% of 1-RM for seven machine-weight exercises. The greatest difference in RTFs occurred between the leg curl and leg press exercises at 40% of 1-RM (see Tables 2.8 and 2.9). In addition, a significant difference in RTF numbers was also observed between the knee extension and leg press exercises at 40% of 1-RM. However, when the loads reached 80% of 1-RM there was generally much less variability in RTF numbers between the exercises.

Faigenbaum et al.(1998) also investigated the number of RTFs that could be performed for different exercises, this time at 50% and 75% of 1-RM for the bench press and leg press exercises. Using 21 children (mean age 10.4 ± 1.2 years) the authors found that the greatest difference in RTFs occurred at 50% of 1-RM (leg

Table 2.8: Number of Repetitions Performed at Selected Percentages of the 1-RM for Seven Exercises (mean ± SD)

Exercise	40% of 1-RM	60% of 1-RM	80% of 1-RM
Untrained Males			
Leg Press	80.1 ± 47.9 A	33.9 ± 14.2 A	15.2 ± 6.5 A
Bench Press	34.9 ± 8.8 B	19.7 ± 4.9 B	9.8 ± 3.6 B
Lat Pulldown	41.5 ± 16.1 B	19.7 ± 6.1 B	9.8 ± 3.9 B
Knee Extension	23.4 ± 5.1 C	15.4 ± 4.4 C	9.3 ± 3.4 BC
Sit-Up	21.2 ± 7.5 C	15.0 ± 5.6 C	8.3 ± 4.1 BCD
Arm Curl	24.3 ± 7.0 C	15.3 ± 4.9 C	7.6 ± 3.5 CD
Leg Curl	18.6 ± 5.7 C	11.2 ± 2.9 D	6.3 ± 2.7 D

Letters indicate significantly different groupings (alpha level = 0.05), same letter indicates no difference.

Modified from Hoeger, Barette, Hale, & Hopkins (1987)

Table 2.9: Number of Repetitions Performed at Selected Percentages of the 1-RM for Seven Exercises (mean ± SD)

Exercise	40% of 1-RM	60% of 1-RM	80% of 1-RM
Trained Males			
Leg Press	77.6 ± 34.2 A	45.5 ± 23.5 A	19.4 ± 9.0 A
Bench Press	42.9 ± 16.0 B	23.5 ± 5.5 B	12.2 ± 3.72 B
Lat Pulldown	38.8 ± 8.2 B	22.6 ± 4.4 B	12.2 ± 2.87 B
Knee Extension	32.9 ± 8.8 BCD	18.3 ± 5.6 BC	11.6 ± 4.47 B
Sit-Up	27.1 ± 8.76 CD	18.9 ± 6.8 BC	12.2 ± 6.42 B
Arm Curl	35.3 ± 11.6 BC	21.3 ± 6.2 BC	11.4 ± 4.15 B
Leg Curl	24.3 ± 7.9 D	15.4 ± 5.9 C	7.2 ± 3.08 C
Untrained Females			
Leg Press	83.6 ± 38.6 A	38.0 ± 19.2 A	11.9 ± 7.0 A
Bench Press	45.9 ± 19.9 B	23.7 ± 10.0 B	10.0 ± 5.6 AB
Lat Pulldown	No data*	20.3 ± 8.2 B	10.3 ± 4.2 AB
Knee Extension	19.2 ± 5.3 C	13.4 ± 3.9 C	7.9 ± 2.9 BC
Sit-Up	20.2 ± 11.6 C	13.3 ± 8.2 C	7.1 ± 5.2 C
Arm Curl	24.8 ± 11.0 C	13.8 ± 5.3 C	5.9 ± 3.6 C
Leg Curl	16.4 ± 4.4 C	10. 5 ± 3.4 C	5.9 ± 2.6 C
Trained Females			
Leg Press	146.1 ± 66.9 A	57.3 ± 27.9 A	22.4 ± 10.7 A
Bench Press	81.3 ± 41.8 B	25.2 ± 7.9 CB	10.2 ± 3.9 C
Lat Pulldown	No data*	27.9 ± 7.9 B	14.3 ± 4.4 B
Knee Extension	28.5 ± 10.9 C	16.5 ± 5.3 DE	9.4 ± 4.3 CD
Sit-Up	34.5 ± 16.8 C	20.3 ± 8.1 CD	12.0 ± 6.5 BC
Arm Curl	33.4 ± 10.4 C	16.3 ± 5.0 DE	6.9 ± 3.1 DE
Leg Curl	23.2 ± 7.7 C	12.4 ± 5.1 E	5.3 ± 2.6 E

Letters indicate significantly different groupings (alpha level = 0.05), same letter indicates no difference. *No data due to resistance limitations on machine-weights.

Modified from Hoeger, Hopkins, Barette & Hale (1990) press: 87.2 ± 56.5, bench press: 39.2 ± 19.4). In contrast, the loads at 75% 1-RM produced less variability in RTF numbers between these exercises (leg press: 18.2 ± 11 repetitions, bench press: 13.4 ± 4.3 repetitions).

Based on these studies, it appears that there was less variability in the number of RTFs performed for different exercises when greater percentage of 1-RM loads were utilized. This is important because reduced variability in the number of RTFs performed for different exercises might improve the consistency of 1-RM predictive accuracy across those exercises.

2.6.1.4. Summary

There are three important conclusions that can be drawn from this section. Firstly, studies have shown that by using a variety of techniques, 1-RM performance can be accurately predicted with both heavy loads (less RTFs) and light loads (more RTFs). Secondly, when considering the generic 1-RM prediction equations being investigated in this thesis, it is clear from the literature that these equations are more accurate with loads that produce RTFs ≤ 10. Finally, it appears that higher loads (e.g. ≥ 75% of 1-RM) should be employed when using generic 1-RM prediction equations with different exercises because this is likely to reduce the variability in RTF numbers that can occur across the exercises.

2.6.2. Speed of Repetitions

The 1-RM prediction equations being investigated in this thesis utilize the number of RTFs that can be performed at selected percentages of 1-RM. Importantly, it has been demonstrated that the velocity at which a lift is performed can alter this relationship. Using 13 healthy males (21.7 ± 1.0 years), Sakamoto & Sinclair (2006) had each subject perform RTFs on a machine-weight bench press at different intensities (40%, 50%, 60%, 70% and 80% of 1-RM) across four different velocities. The authors reported that lifting velocity significantly changed the relationship between the selected percentage of 1-RM and the number of RTFs performed ($p < 0.001$), with the slow velocity (2.8 seconds down/2.8 seconds up) producing the lowest number of RTFs. For example, with a 69% of 1-RM load the slow velocity produced six RTFs.

In contrast, the medium velocity (1.4 seconds down/1.4 seconds up) produced nine RTFs and the fast (1.0 second down/1.0 second up) and ballistic (as fast as possible) velocities both produced 10 RTFs. Importantly, for the prediction equations being investigated in this thesis, the estimated percentages of 1-RM that produce 10 RTFs range from 74.2% to 81.7% (see Table 2.5). This would suggest that faster lifting velocities would be more likely to generate accurate 1-RM estimates when using these equations. Finally, Sakamoto & Sinclair (2006) reported that the discrepancy between RTFs performed at slower and faster velocities was much greater at lower percentages of 1-RM. This finding would appear to provide further support for the use of heavier loads (which generate RTFs ≤ 10) with generic 1-RM prediction equations.

2.6.3. Level of Training

It has been suggested that the accuracy of 1-RM prediction equations might be different in weight-trained and untrained individuals (Braith et al., 1993). Prediction equations are based on the relationship between maximal muscle strength and the number of RTFs that can be performed at selected percentages of 1-RM. Importantly, it could be argued that RTFs represent muscular fatigue. In this context fatigue could be described as a process that results in the inability to produce the muscular force required to lift a sub-maximal load through a specified range of motion. It has been suggested that muscle fatigue involves both central and peripheral mechanisms (Fitts, 1994). The central components that influence muscle fatigue are thought to include decreases in cortical drive, changes in motor unit firing rates, decreases in the excitability of alpha-motoneurons and possibly the depletion of neurotransmitters at central synapses (Fitts, 1994; Molloy, 2005). The peripheral components that influence muscle fatigue are thought to involve the composition of muscles with respect to fibre types, changes in the concentrations of metabolites and electrolytes in and around muscle cells, alterations in the release, reuptake and binding of calcium ions and changes in metabolic energy supplies (Fitts, 1994; Molloy, 2005). While resistance training has been repeatedly shown to improve 1-RM strength (Hakkinen et al., 2003; Kalapotharakos, Michalopoulos et al., 2005; Stone et al., 2000), it has also been shown to increase fatigue resistance while performing RTFs, probably through alterations in both central and peripheral mechanisms (Braith et al., 1993; Hoeger et al., 1990; Pick & Becque, 2000). However, if resistance training caused a significantly greater relative increase in either 1-RM strength or fatigue resistance, then the accuracy of 1-RM prediction equations might differ for trained and untrained subjects. Importantly, some studies have demonstrated that the number of RTFs performed at selected percentages of 1-RM may differ for trained and untrained individuals. For example, using 129 subjects Hoeger, Hopkins, Barette, & Hale (1990) demonstrated that trained individuals were generally able to perform more RTFs than untrained individuals at 40%, 60% and 80% of 1-RM across a range of exercises (see Tables 2.8 and 2.9). The authors reported that the disparity in RTFs between the exercises was smaller with the 80% of 1-RM loads (ranging from 0.9 to 4.2 repetitions for males and -0.6 to 10.5 repetitions for females) when compared to the other loads. However, it should be recognized that even small differences in RTF numbers at 80% of 1-RM could lead to discrepancies in the accuracy of 1-RM prediction equations. Therefore, the results of this study suggest that the accuracy of 1-RM prediction equations might be different for trained and untrained subjects.

Braith, Graves, Leggett, & Pollock (1993) also investigated the effect of training on the relationship between 1-RM strength and the number of RTFs preformed with a sub-maximal load. The authors randomly assigned 33 males and 25 females to a group that trained 2-3 times a week for 18 weeks (one set of 7-10 RTFs on a knee extension machine; n = 47) or a control group (n = 11). One repetition maximum and 7-10 RTF tests were performed pre- and post-training. The authors reported that the training group increased their 1-RM and 7-10 RTF performance by 31.7% and 51.4%, respectively ($p \leq 0.01$), while the control group showed no significant changes. In addition, the authors reported that training increased relative 7-10 RTF strength (68.4% of 1-RM at pre-training and 79.1% of 1-RM at post-training). However, it should be recognized that relative 7-10 RTF strength could potentially have been affected by movement from the upper end to the lower end of the 7-10 RTF spectrum over the two testing sessions. In any case, based on the pre-training data the authors developed a 1-RM prediction equation which had a SEE of 9.3 kg (10.6% of the group mean). When this equation was applied to the post-training data the SEE was similar (9.4 kg) but the total error (TE) was 25.6 kg. The authors suggested that the considerable difference between the SEE and TE was indicative of a systematic error that resulted in an overestimation of 1-RM performance by approximately 21 kg in the trained subjects. The authors therefore developed a second prediction equation from the post-training data. When the authors compared the pre- and post-training equations they found that the slopes and intercepts were significantly different ($p < 0.01$). Based on these results, the authors suggested that a prediction equation developed using untrained subjects was not appropriate for trained subjects because it resulted in the overestimation of 1-RM performance. However, it should be recognized that the training regime used in this study involved performing the same RTF range that was used for testing (7-10 RTFs). This may at least partially explain the greater relative increase in RTF performance compared to 1-RM performance. On the contrary, it is possible that a periodised training schedule (generally beginning with high-volume/low-intensity training and over time progressing to high-intensity/low-volume training) might have resulted in more consistent changes in both 1-RM and 7-10 RM performance. In addition, the equations developed by Braith, Graves, Leggett, & Pollock (1993) used only the load lifted for the 7-10 RTF range to predict 1-RM performance. In contrast, generic 1-RM prediction equations utilize both the sub-maximal load and the *exact* number of RTFs performed at that load to estimate maximal strength. Therefore, it is possible that generic prediction equations might have demonstrated similar accuracy in both the trained and untrained groups, although this was not investigated.

Finally, Pick & Becque (2000) investigated the effect of resistance training on vastus medialis and vastus lateralis muscle activation and the number of RTFs that could be performed at 85% of 1-RM during a back squat exercise. The authors found that trained subjects ($n = 9$; 1-RM = 184.20 ± 9.87 kg) had significantly greater 1-RM strength than untrained subjects ($n = 7$; 1-RM = 120.20 ± 8.04 kg). In addition, the trained subjects exhibited significantly greater vastus medialis activation than the untrained subjects during 1-RM testing, although vastus lateralis activation was similar across the groups. The trained subjects also performed significantly more RTFs than the untrained subjects at 85% of 1-RM (9.67 ± 0.91 RTFs vs. 7.14 ± 0.74 RTFs, respectively) and exhibited significantly greater vastus medialis and vastus lateralis muscle activation during the RTF testing. Based on these findings, the authors suggested that increased muscle activation might have partially explained the greater relative sub-maximal lifting capacity of the trained individuals in this study. In addition, these findings appear to provide further evidence that trained individuals may generally perform more RTFs than untrained individuals, at the same percentages of 1-RM. If this is the case, then the accuracy of generic 1-RM prediction equations is likely to be different for trained and untrained subjects, and perhaps also for subjects with muscle strength deficits due to pathology.

In contrast to the investigations described above, two studies have demonstrated that a generic 1-RM prediction equation was accurate in both trained and untrained populations. Mayhew, Ball, & Bowen (1992) investigated the accuracy of the Mayhew et al. equation when estimating 1-RM bench press performance before and after 14 weeks of aerobic and resistance training. Using 171 college students (70 males and 101 females) the authors assessed 1-RM performance prior to training. They then randomly assigned each subject a load corresponding to 55-95% of their 1-RM and asked them to perform as many repetitions as possible in one minute. Post-training the 1-RM testing was repeated and each subject again performed as many repetitions as possible with a load that was calculated using the same percentage they were assigned pre-training. The authors reported that the 1-RM weights and the RTF weights increased by 13.7% for males ($p \leq 0.05$) and 25.9% for females ($p \leq 0.01$), post-training. However, the authors also reported that the number of RTFs that could be completed in one minute pre-training did not change significantly post-training ($p > 0.05$). With regard to the Mayhew et al. equation, the authors reported pre- and post-training SEEs of 6.6 kg and 5.7 kg, respectively, for the males and 2.9 kg and 3.5 kg, respectively, for the females. In addition, the coefficients of variation for the pre- and post-training tests were reported as 9.6% and 7.3%, respectively, for the males and 9.8% and 9.5%, respectively, for the females, which the authors suggested was indicative of equal variability around the predicted mean for each gender. Based on these findings, the authors argued that the Mayhew et al. equation demonstrated a similar level of accuracy in both trained and untrained subjects.

In a second study, Mayhew, Ball, Arnold, & Bowen (1992) cross-validated the Mayhew et al. equation using the bench press exercise, this time in male high school athletes ($n = 25$), male high school non-athletes ($n = 74$) and male college football players ($n = 45$). Importantly, the college football players had completed a 10 week high intensity (80-95% of 1-RM) / low volume (2-8 repetitions) resistance training program prior to testing. The authors reported that the Mayhew et al. equation non-significantly ($p > 0.05$) overestimated 1-RM performance for both the high school athletes and non-athletes by averages of 1.4% (± 4.0) and 1.9% (± 8.1), respectively. In addition, the SEEs were reported as ± 4.1 kg and ± 5.8 kg for the athletes and non-athletes, respectively. For the college football group, the authors reported that the Mayhew et al. equation non-significantly underestimated 1-RM performance by an average of -0.9 % (± 4.4), with a SEE of ± 5.0 kg. Based on these findings, the authors suggested that the Mayhew et al. equation demonstrated a similar level of accuracy in both trained and untrained individuals.

In a later study, Mayhew et al. (1995) investigated the accuracy of six prediction equations when estimating 1-RM performance in various groups of trained and untrained males. Unfortunately, the authors acknowledged that the directions given for RTF performance differed among the groups and therefore invalidated any evaluation of the possible effects of training on muscle endurance and 1-RM prediction. Therefore, the results of this study are unlikely to meaningfully contribute to the current discussion. In addition, comparisons between other studies which have investigated the accuracy of 1-RM prediction equations using either trained or untrained subjects are unlikely to be useful due to methodological differences with respect to factors such as load, equipment and exercise type.

Finally, a study by Sebelski, Wilson, Mayhew, & Ball (1994) has also provided support for the contention that resistance training does not alter the relationship between maximal muscle strength and the number of repetitions that can be performed at selected percentages of 1-RM. Using 59 college students enrolled in a fitness class, the authors measured bench press 1-RM performance and the number of repetitions that could be performed in one minute at 60% of 1-RM, before and after 14 weeks of training. The resistance training program consisted of one set of 8-12 repetitions performed for the bench press exercise and six other unspecified upper and lower body exercises, three times a week. The authors reported that 1-RM bench press performance increased significantly by an average of 6.7 kg (± 5.6 kg) or 9.8% following training ($p < 0.05$). In addition, the loads used for determining muscular endurance increased significantly by an average of 4.1 kg (± 3.6 kg), due to the increases in 1-RM values. However, the authors reported that the number of repetitions performed in one minute was not significantly different following training. Based on these findings, the authors suggested that resistance training did not change the number of repetitions that could be performed at a selected percentage of 1-RM (60%). However, this study has a number of limitations. Firstly, some of the subjects in this study were resistance trained, while others were untrained. Secondly, only one set of 8-10 repetitions was performed during training, which is unusual considering that many resistance training programs utilize 3-5 sets for this repetition range. Finally, the endurance test used in this study involved performing as many repetitions as possible in one minute using a 60% of 1-RM load, with rest periods permitted during this time. This procedure is significantly different from the RTF procedures typically used with 1-RM prediction equations. Therefore, in the context of generic 1-RM prediction equations, the results of this study should be viewed with caution.

Based on the contrasting results of the studies described above, it appears that some investigations have supported the contention that resistance training can alter the relationship between muscular endurance and maximal strength, while others have refuted it. However, it should be recognized that the type of resistance training being undertaken could have a significant influence on this issue. For example, some studies have demonstrated that different training regimes can have diverse effects on relative changes in 1-RM strength and muscular endurance. Stone & Coulter (1994) examined the effects of high resistance/low repetition (HR/LR) training (3 sets of 8-10 RTFs), medium resistance/medium repetition (MR/MR) training (2 sets of 15-20 RTFs) and low resistance/high repetition (LR/HR) training (1 set of 30-40 RTFs) on 1-RM strength and the number of RTFs that could be performed at selected percentages of pre- and post-training 1-RMs. The authors reported that for the bench press exercise the HR/LR, MR/MR and LR/HR groups demonstrated post-training increases in 1-RM strength of 18.9%, 16.7% and 11.6%, respectively. In addition, the authors reported that, for the bench press, the HR/LR group demonstrated a decrease of 6.4% for RTFs performed at 45% of 1-RM, while the MR/MR and LR/HR groups exhibited increases of 10.5% and 9.0%, respectively. For the squat exercise, the authors reported that the HR/LR, MR/MR and LR/HR groups demonstrated increases in 1-RM strength of 33.0%, 30.9% and 25.1%, respectively and increases in RTFs performed at 55% of 1-RM of 30.7%, 12.9% and 32.6%, respectively. Although the percentages of 1-RM used for the RTF testing were relatively low (45% and 55%), these results appear to demonstrate that relative changes in 1-RM strength and muscular endurance differed depending on the training regime being followed and the type of exercise being performed. With respect to the accuracy of 1-RM prediction equations the results of this study suggest that if a prediction equation was accurate for the bench press prior to training, it would probably have produced a similar level of accuracy in all three groups post-training based on the relatively small percentage changes in RTF performance (-6.4%, 10.5% and 9.0%). In contrast, if a prediction equation was accurate for the squat prior to training, it may have produced a similar level of accuracy for the MR/MR group post-training (12.9% increase in RTF performance), but would probably have overestimated 1-RM performance in the HR/LR and LR/HR groups (30.7% and 32.6% increases in RTF performance).

In a more recent study, Campos et al. (2002) investigated the effects of different training regimes on a number of parameters including muscular endurance and 1-RM performance for the leg press, knee extension and squat exercises. The authors randomly divided subjects into four training groups consisting of a low repetition group (Low Rep, n=9) performing 3–5 RTFs for four sets of each exercise, an intermediate repetition group (Int Rep, n=11) performing 9–11 RTFs for three sets, a high repetition group (High Rep, n=7) performing 20–28 RTFs for two sets and a non-exercising control group (Con, n=5). Unfortunately however, specific percentage changes in 1-RM and RTF performance were only described for the leg press exercise. The authors reported that 1-RM performance for the leg press increased by 61% for the Low Rep group, 36% for the Int Rep group, 32% for the High Rep group and 6% for the Con group. In contrast, RTFs actually decreased by 20% for the Low Rep group and 19% for the Con group but improved by 94% for the High Rep group and 10% for the Int Rep group. Although the percentage of 1-RM used for the RTF testing in this study was fairly low (60%), these results appear to support the contention that relative changes in 1-RM strength and muscular endurance may differ depending on the training regime being followed. In turn, it appears likely that the accuracy of a 1-RM prediction equation might have changed if it was applied to some of these groups before and after training. For example, the Low Rep group performed 20% less RTFs for the leg press at 60% of 1-RM, following training. If a 1-RM prediction equation had been accurate pre-training then it would probably have underestimated 1-RM performance post-training. In contrast, the High Rep group performed 94% more RTFs at 60% of 1-RM following training. If a 1-RM prediction equation had been accurate pre-training then it would probably have overestimated leg press 1-RM performance post-training.

In conclusion, it appears that studies investigating the impact of resistance training on the accuracy of 1-RM prediction equations have produced contradictory results. Some studies have suggested that resistance training can alter the relationship between maximal muscle strength and the number of RTFs that can be performed at selected percentages of 1-RM, while other studies have refuted this contention. However, it appears that the type of resistance training being undertaken could have a significant impact on this issue and may partially explain the equivocal findings to date. Nevertheless, it appears that 1-RM prediction equations are generally accurate with subjects who are not resistance trained. Importantly, it could be argued that even trained individuals who have developed significant muscle weakness due to arthritis or injury could be re-categorised as untrained, at least for the affected muscle group(s). However, it is less clear whether 1-RM prediction equations would be accurate for the contralateral unaffected muscle group(s) in these subjects or whether 1-RM prediction equations would remain accurate following resistance training for the affected muscle group(s). Until issues such as these are addressed, the use of 1-RM prediction equations as means of monitoring maximal strength changes during a resistance training program could be questioned.

2.6.4. Exercise Type & Equipment

For 1-RM prediction equations to be truly useful in clinical settings they would need to be accurate across a range of exercises and equipment to permit the testing of different muscle groups. Although the originators of at least four equations (the Lander, Lombardi, O'Connor and Wathen equations) apparently suggested that their equations were applicable across a variety of exercises, many of the prediction equations being evaluated in this thesis appear to have been developed using data from the free-weight bench press exercise only (Berger, 1961; Brzycki, 1993; Mayhew, Ball, Arnold et al., 1992; Wood et al., 2002). This may be an issue because 1-RM prediction equations are based on the relationship between specific percentages of 1-RM and the number of RTFs that can be performed at those loads. Therefore, if this relationship varies significantly across different types of equipment (free vs.

machine weights) or across different exercises (e.g. knee extension vs leg press), then the accuracy of 1-RM prediction equations might also vary depending on the exercise and/or equipment being utilized. Importantly, the results of some studies have suggested that the number of RTFs completed at selected percentages of 1-RM may vary depending on the exercise being performed. For example, Hoeger, Barette, Hale, & Hopkins (1987) used 38 untrained male subjects to determine the number of RTFs that could be performed at 40%, 60% and 80% of their 1-RMs for each of seven different machine-weight exercises. The authors found that the number of RTFs the subjects could perform at these percentages varied significantly across the exercises (see Table 2.8).

In a repeat study, this time using 40 untrained females, 25 trained males and 26 trained females, Hoeger, Hopkins, Barette, & Hale (1990) again reported that the number of RTFs the subjects could perform at 40%, 60% and 80% of their 1-RMs varied significantly across the same seven exercises (see Table 2.9). However, on closer analysis it is important to note that within each group there were no significant differences in most cases between the number of RTFs performed for the bench press, lat pulldown, knee extension and sit-up exercises at 80% of 1-RM. In addition, the number of RTFs performed by trained males for the arm curl exercise were not significantly different from those performed for the bench press, lat pulldown, knee extension and sit-up exercises, and nor were they significantly different from the number of RTFs performed by untrained males for the knee extension and sit-up exercises. Importantly, for the majority of the exercise groupings just described, the RTF range at 80% of 1-RM was 7.6 to 12.2 repetitions (excluding 14.3 RTF for the trained female lat pulldown). These figures appear to be comparable to the range of RTFs that the prediction equations being investigated in this thesis generate at 80% of 1-RM (approximately 7 to 11 repetitions – see Table 2.7). This observation is also important because these studies were performed using machine-weights on a Universal Gym, rather than free-weights. Therefore, it could be argued that the prediction equations being investigated in this thesis might have produced more accurate estimates of 1-RM performance for the machine-weight bench press, lat pulldown, knee extension, sit-up and possibly arm curl exercises, compared to the machine-weight leg press and leg curl exercises. In the context of the current study these findings are particularly important because it suggests that the accuracy of 1-

RM prediction equations might be significantly different for machine-weight leg press and knee extension exercises.

Faigenbaum et al. (1998) also used machine-weight exercises to evaluate the relationship between RTFs and selected percentages of 1-RM in healthy children. The authors measured 1-RM performance for the bench press and leg press exercises in 8 girls and 13 boys (10.4 ± 1.2 years) and then determined the number of RTFs that could be performed at 50% and 75% of 1-RM for each exercise. The authors reported that for the leg press and bench press, the subjects performed 87.2 (± 56.5) and 39.2 (± 19.4) RTFs respectively at 50% of 1-RM, while they performed 18.2 (± 11.0) and 13.4 (± 4.3) RTFs respectively at 75% of 1-RM. Based on these findings, the authors argued that the number of RTFs performed by children at selected percentages of 1-RM were different for machine-weight leg press and bench press exercises.

In a study that used free-weight exercises, Ware, Clemens, Mayhew, & Johnston (1995) evaluated the accuracy of using four prediction equations to estimate bench press and squat 1-RM performance in 45 college football players. Although the subjects self-selected loads in this study, the authors reported that on average 13.9 (± 2.1) RTFs were performed at 71.3% (± 4.9%) of 1-RM for the bench press exercise, while 17.4 (± 3.2) RTFs were performed at 68.0% (± 4.5%) of 1-RM for the squat. While not specifically discussed by the authors, these findings suggest that the number of RTFs performed at similar percentages of 1-RM is different for the bench press and squat exercises. However, it seems that even a small difference in the percentage of 1-RM being used may alter the number of RTFs that can be performed. For example, Adams (1994) contended that an increase of 2% in the percentage of 1-RM resulted in a concurrent decrease of one RTF, when RTFs numbered between two and twenty. If this principle is applied to Ware et al.'s results, the number of RTFs performed for the squat would decrease to around 15.8 repetitions at 71.3% of 1-RM and more closely approximate the 13.9 RTFs performed for the bench press exercise at the same percentage of 1-RM. Nevertheless, the difference in RTFs between the bench press and squat exercises appears to have influenced the accuracy of the four prediction equations evaluated in Ware et al.'s study. The results demonstrated that the SEEs and total errors of the equations were significantly lower for the bench press than for the squat (SEE: bench press 5.8- 6.7%, squat 4.9-11.7%; total error: bench press 6.6-13.6%, squat 8.6-25.6%). Therefore, this study appears to support the contention that the number of RTFs performed at specific percentages of 1-RM might differ between free-weight bench press and squat exercises and consequently influence the accuracy of 1-RM prediction equations.

In another study that used free-weights, Mayhew, Schutter, & Bemben (1995) investigated the relationship among RTFs for the bench press, seated press and biceps curl exercises. In addition, the authors evaluated the accuracy of the Mayhew et al. equation when predicting 1-RM performance for these exercises. The authors randomly assigned a 1-RM percentage (ranging from 55% to 95%) to 55 untrained college-aged males which each subject then used to perform RTFs for all three exercises. The authors reported that the mean number of RTFs performed for the biceps curl (12.7 ± 5.4) and bench press (12.4 ± 6.6) were similar, although both differed significantly from the seated press (10.2 ± 5.6). In addition, the authors reported that while the Mayhew et al. equation accurately estimated 1-RM performance for the bench press ($r = 0.96$, $t = 0.74$, SEE = 6.7 kg) and biceps curl ($r = 0.87$, $t = 0.91$, SEE = 3.7 kg), it significantly underestimated 1-RM performance for the seated press ($r = 0.88$, $t = 3.08$, SEE = 5.1 kg). Surprisingly, the authors concluded that although the number of RTFs performed for these exercises varied, the data could still be used to accurately estimate 1-RM performance. However, if the Mayhew et al. equation significantly underestimated 1-RM performance for the seated press, it is unclear how such a conclusion could be defended.

In a more recent study, Kravitz, Akalan, Nowicki, & Kinzey (2003) determined the number of RTFs that could be performed for the free-weight squat, bench press and deadlift exercises at 70%, 80%, and 90% of 1-RM. Unfortunately the authors only reported the mean number of repetitions performed at 70% of 1-RM for the squat (13 ± 3.18 reps) and the bench press (16 ± 2.38 reps) and at 80% of 1-RM for the deadlift (12 ± 3.17 reps). Nevertheless, it can be seen that the number of RTFs performed at 70% of 1-RM was different for the bench press and squat exercises. However, if the number of RTFs performed for the deadlift is adjusted based on the Adams (1994) principle (an increase of 1 RTF for each 2% decrease in the percentage of 1-RM), then a reduction to 70% of 1-RM would theoretically increase the number of RTFs performed to approximately seventeen. If such an adjustment is sound then it could be argued that, in this group of subjects, the number of RTFs performed at 70% of 1-RM would have been similar for the bench press and deadlift, but significantly different for the squat. Therefore, based on these findings and assumptions, it is possible that the accuracy of a 1-RM prediction equation would be similar for the bench press and squat, but differ for the deadlift. However, this issue was not specifically investigated in the Kravitz, Akalan, Nowicki, & Kinzey (2003) study.

In another recent study, Izquierdo, Gonzalez-Badillo, Hakkinen, Ibanez, Kraemer, Altadill, Eslava, & Gorostiaga (2006) used 36 male athletes to determine the number of RTFs that could be performed for the free-weight bench press and half squat exercises at selected percentages of 1-RM. For the bench press the authors reported that 8.8 (± 2) RTFS, 11.4 (± 2) RTFs, 13.8 (± 2) RTFs, and 17.25 (± 2) RTFs were performed at 75%, 70%, 65% and 60% of 1 RM, respectively. For the half squat the authors reported that 10.4 (± 1) RTFs, 14.2 (± 2) RTFs, 18.6 (± 2) RTFs, and 21.5 (± 2) RTFs were performed at 75%, 70%, 65% and 60% of 1RM, respectively. Based on these results, the authors stated that the mean RTFs performed for the half squat at selected percentages of 1-RM were significantly higher than those performed for the bench press ($p < 0.001$). Importantly, the authors suggested that the number of RTFs performed for the half squat may have been slightly inflated because a partial ROM (thigh parallel to the floor) was used, rather than a full squat. Nevertheless, these findings suggest that the accuracy of a 1-RM prediction equation might be different for the bench press and half squat exercises, although this was not specifically investigated in the Izquierdo et al (2006) study.

Finally, Reynolds, Gordon, & Robergs (2006) used 70 subjects (34 men, 36 women; 18–69 years of age) to investigate the decrease in the load lifted at 1, 5, 10, and 20 RTFs for the free-weight bench press and the machine-weight leg press exercises. In addition, 1-RM prediction equations were developed from this data. The authors reported that the mean percentages of 1-RM for the leg press were 85.91%, 70.10%, and 51.58% for the 5, 10, and 20 RTF conditions, respectively. In contrast, the mean percentages of 1-RM for the bench press were 87.45%, 75.65% and 61.61% for the 5, 10, and 20 RTF conditions, respectively. Based on these results, it appears that the percentage of 1-RM that can be lifted at selected RTFs differs between the free-weight bench press and the machine-weight leg press, although the difference is less when RTFs are ≤ 10. Importantly, Reynolds, Gordon, & Robergs (2006) reported that a bench press specific prediction equation they developed from the data yielded similar results to the Landers and Mayhew et al. 1-RM prediction equations. In contrast, a leg press specific equation they developed produced meaningfully different results when compared to these equations. Based on these findings, the authors suggested that greater predictive accuracy might be achieved with exercise specific 1-RM prediction equations.

In contrast to the studies described above, some investigations have found minimal variation in RTFs across different exercises., Morales & Sobonya (1996) found that the number of RTFs performed at specific percentages of 1-RM were consistent across the free-weight bench press, squat and power clean exercises (Table 2.10). In this study, 23 male college athletes were used to determine the number of RTFs that could be performed at 70%, 75%, 80%, 85%, 90% and 95% of 1-RM for each exercise. Importantly, an ANOVA analysis of the data revealed that the type of lift did not have any effect of the number of RTFs performed at any of the 1-RM percentages. In addition, qualitative comparisons appear to indicate that the ranges of RTFs performed in this study are similar to the ranges of RTFs that many prediction equations generate at the same percentages of 1-RM (see Table 2.5). Therefore, it could be argued that the accuracy of a 1-RM prediction equation might have been similar for the bench press, squat and power clean exercises, although this was not specifically investigated in the Morales & Sobonya (1996) study.

Table 2.10: Repetitions Performed at Selected Percentages of 1-RM for the Bench Press, Squat and Power Clean

Percentage of 1-RM	Bench Press	Squat	Power Clean
70%	13.35 ± 1.99	13.48 ± 2.33	13.61 ± 2.57
75%	11.04 ± 1.15	10.61 ± 1.12	11.52 ± 1.83
80%	9.22 ± 2.09	8.44 ± 1.44	9.26 ± 1.76
85%	6.00 ± 1.28	6.48 ± 1.31	7.04 ± 1.66
90%	4.04 ± 1.02	4.57 ± 0.90	4.57 ± 1.50
95%	2.17 ± 0.89	2.39 ± 0.72	2.57 ± 1.16

Modified from Morales & Sobonya (1996).

In a more recent study, Baker (2004) investigated the accuracy of a prediction table when used to estimate 1-RM performance for the free-weight bench press and weighted pull-up exercises. For the bench press (n = 34), the authors reported that 10.1 (± 4.8) RTFs were performed at 76.6% (± 8.8) of 1-RM, while the table predicted that 9.8 (± 5.1) RTFs would be performed at this percentage of 1-RM. For the weighted pull-up (n = 23), 11.5 (±4.3) RTFs were performed at 74.0% (±7.1) of 1-RM, while the table predicted that 11.1 (±4.3) RTFs would be performed at this percentage of 1-RM. Importantly, these results appear to show that similar numbers of RTFs were performed for the free-weight bench press and weighted pull-up exercises, at similar percentages of 1-RM.

Based on the studies described above, it appears that the number of RTFs completed at selected percentages of 1-RM might vary for some exercises but not for others. In turn, these findings suggest that the accuracy of generic 1-RM prediction equations might vary depending on the exercise being performed. Importantly, a number of studies have specifically investigated the accuracy of different 1-RM prediction equations across a range of exercises. Some of these studies have suggested that 1-RM prediction equations are accurate for a number of different exercises. For example, Akinpelu, Iyaniwura, & Ajagbe (2001) investigated the accuracy of Berger's table when estimating free-weight biceps curl 1-RM performance in a group consisting of 50 males and 50 females. The reported values for estimated and actual 1-RM performance were 12.23 kg (± 1.85 kg) and 13.24 kg (± 1.56 kg), respectively, for males and 6.98 kg (± 1.08 kg) and 7.68 kg (± 0.97 kg), respectively, for females. From these results, the mean differences between estimated and actual 1-RM performance can be calculated as 1.01 kg (7.6%) for men and 0.7 kg (9.1%) for women. For the total sample, the reported values for estimated and actual 1-RM performance were 9.61 kg (± 3.04) and 10.46 kg (± 3.08) respectively, resulting in a mean underestimation of 0.85 kg (8.1%). Based on these results, the authors suggested that Berger's table appeared to be accurate in estimating 1-RM performance for the biceps curl exercise in healthy young adults.

In a more recent study, Taylor & Bandy (2005) used 15 college-aged subjects to assess the accuracy of the Brzycki equation when used to estimate 1-RM performance for shoulder internal rotation. Testing was performed using a weighted pulley system in both supine (shoulder adducted to 0º) and prone positions (shoulder abducted to 90º). RTFs < 10 were used and the procedures were performed twice to determine test-retest intrarater reliability. The authors averaged the predicted 1-RM values from the two sessions and reported mean predicted 1-RM values of 98.34 Newtons (N) (± 38.18) for the supine position and 86.45 N (± 32.25) for the prone position. Reported actual 1-RM values were 97.11 N (± 38.14) for the supine position and 83.15 N (± 33.78) for the prone position. Thus, the difference between predicted and actual 1-RM performance was an overestimation of 1.23 N (1.3%) for the supine position and an overestimation of 3.3 N (3.8%) for the prone position. In addition, the authors reported that a comparison between predicted shoulder internal rotation 1-RM performance and actual 1-RM performance demonstrated an ICC of 0.99 (95% CI = 0.98-0.99) for the supine position and 0.97 (95% CI = 0.92-0.99) for the prone position. Based on these findings, the authors argued that the Brzycki equation was accurate for estimating shoulder internal rotation 1-RM performance in supine and prone positions, using RTFs < 10.

In another recent study, Lovelace (2005) used 20 subjects with a history of significant Achilles tendon or plantarflexor unit injury to investigate the accuracy of eight prediction equations when used to estimate unilateral 1-RM performance for a machine-weight calf raise exercise. The author reported that all of the equations displayed high accuracy and low error for both limbs. The largest reported relative difference between experimental and predicted 1-RMs across all of the equations and both limbs was 2.98% for the O'Connor equation when used for the injured limbs. In addition, Bland and Altman graphs of the data indicated that there were no systemic changes in error across the range of values. Finally, the author reported that typical errors were small for all of the equations. The greatest typical error was reported for the Lombardi equation when used with the control limb (3.39 kg, 2.3%) and the injured limb (3.88 kg, 2.9%). In contrast, the smallest typical error was reported for the Epley equation when used with the control limb (2.59 kg, 1.7%) and for the Brzycki and Lander equations when used with the injured limb (2.59 kg 2.0%). Based on these findings, the author argued that all of the equations were relatively accurate, with the predicted 1-RM values differing minimally from actual 1-RM values.

Finally, Kemmler, Lauber, Wassermann, & Mayhew (2006) used 70 resistance trained women (age 57.4 ± 3.1 years) to investigate the accuracy of eight prediction equations when estimating 1-RM performance for four different machine-weight exercises. Repetitions to failure were performed for leg press, bench press, rowing, and leg adduction exercises in the following ranges: 3–5 RTFs, 6–10 RTFs, 11–15 RTFs, and 16–20 RTFs. The authors reported that an equation they developed (KLW equation) accurately predicted 1-RM performance for the four exercises with mean absolute differences between actual 1-RM and predicted 1-RM of 1.5–3.1% and with coefficients of variation of ≤ 3.3%. Therefore, the authors suggested that the accuracy of the equation was independent of the exercise type. In addition, the authors reported that the O'Connor equation produced comparable results with mean absolute differences between actual 1-RM and predicted 1-RM of 1.6–3.5% (except for the 3-6 RTF leg press = 6.2%). Therefore, the authors argued that these findings support the contention that prediction equations can adequately estimate 1-RM performance across different exercises in trained, older female subjects. However, it should be noted that the Brzycki, Epley, Lander, Lombardi, Mayhew et al. and Wathen equations were not accurate when predicting 1-RM performance for these exercises. This finding highlights the fact that, at a specific number of RTFs, the percentages of 1-RM used by the O'Connor and KLW equations to predict 1-RM performance can differ significantly from other equations (see Table 2.5). In addition, these differences can also vary across RTF ranges (see Table 2.5). Based on these differences between prediction equations, it could be argued that since Taylor & Bandy (2005) found the Brzycki equation to be accurate when estimating shoulder internal rotation 1-RM performance, it is unlikely that the O'Connor and KLW equations would have been accurate for this exercise. Similarly, Lovelace (2005) found that the Lander equation was the most accurate prediction method when estimating calf raise 1-RM performance in injured subjects, while the O'Connor equation was one of the least accurate methods. Therefore, it appears unlikely that a single existing generic prediction equation would be accurate for all exercises.

Importantly, the results of a number of studies have supported the contention that the accuracy of 1-RM prediction equations can vary considerably across different exercises. Using 67 untrained college-age subjects, LeSuer, McCormick, Mayhew, Wasserstein, & Arnold (1997) investigated the accuracy of seven equations when predicting 1-RM performance using RTFs ≤ 10 for free-weight bench press, squat and deadlift exercises. For the bench press, the authors reported that only the Mayhew et al. and Wathen equations predicted mean 1-RM values that did not differ significantly from the actual 1-RM value (0.8% underestimation), while the other equations significantly underestimated 1-RM performance by 1 kg to 3.7 kg (1.6% to 6.0%). For the squat, the authors reported that only the Wathen equation predicted a mean 1-RM value that did not differ significantly from the actual 1-RM value (2.2% underestimation), while all the other equations significantly underestimated 1-RM performance by 3.0 kg to 7.5 kg (3.2% to 7.9%). For the deadlift, the authors reported that all of the equations significantly underestimated 1-RM performance by 10.1 kg to 15.3 kg (9.4% to 14.2%). Although the description of the results was limited to mean values, these findings appear to show that the overall accuracy of the seven prediction equations was similar for the bench press and squat, but different for the deadlift exercise.

In another study, Knutzen, Brilla, & Caine (1999) used 51 older subjects to investigate the accuracy of six equations when predicting 1-RM performance using 7-10 RTFs for eleven machine-weight exercises. The authors reported that all of the equations generated mean predicted 1-RM values that were lower than mean actual 1-RM values, for all the exercises. From the reported results, the range of percentage underestimation of 1-RM for each exercise can be calculated as follows: plantarflexion = 0.2%-7.8%; bench press = 2.6%-8.9%; biceps curl = 2.6%-12.0%; hip abduction = 3.4%-10.7%; hip adduction = 4.0%-11.6%; lateral row = 4.3%-9.6%; dorsiflexion = 5.3%-11.5%; hip flexion = 7.0%-14.5%; triceps press = 8.0%-13.9%; supine leg press = 8.4%-14.5%; hip extension = 9.3%-16.6%. Based on these results, it appears that the accuracy of the 1-RM prediction equations varied considerably across these exercises. However, it should be recognized that the O'Connor equation produced the greatest underestimations of 1-RM performance across all of the exercises. In addition, the O'Connor equation appears to have underestimated 1-RM performance by amounts significantly greater than all of the other prediction equations, across all of the exercises. Importantly, if the results from the O'Connor equation are removed, the percentage differences between the mean predicted and actual 1-RM values are less than 10% for all of the exercises except the leg press, hip flexion and hip extension exercises. Interestingly, despite the variation in the accuracy of the prediction equations across the exercises, the authors argued that they were precise enough to determine training loads that would be very similar to those generated from actual 1-RM measurements.

In a more recent study, Wood, Maddalozzo, & Harter (2002) used 49 older adults (53.55 ± 3.34 years) to evaluate the accuracy of seven prediction equations when used to estimate 1-RM performance for ten machine-weight exercises. The authors reported that the average error between predicted and actual 1-RM values (expressed as a percentage of 1-RM) was high for all of the prediction equations, across all of the exercises (range of 12-157%). However, because of the testing methods used by the authors in this study, it should be recognized that many subjects completed RTF numbers > 10. Importantly, when the authors analysed the subjects who performed RTF ≤ 10 separately they found that the average error improved significantly (range of 7-20%). With respect to individual exercises, the range of absolute errors expressed as a percentage of 1-RM were as follows for the subjects who performed RTFs ≤ 10: triceps extension = 7-9%, leg press = 10% for all equations, high latissimus dorsi (lat) pull = 10-12%, leg curl = 10-12%, low lat pull = 12-14%, shoulder press = 12-15%, biceps curl = 13-15%, chest press = 13-17%, incline chest press = 17-20%, and leg extension = 17-20%. Importantly, these results appear to suggest that the accuracy of 1-RM prediction equations varied significantly across a range of machine-weight exercises in this group of older adults.

Finally, only one study could be found which appeared to compare the number of RTFs performed on a machine-weight exercise with the number of RTFs performed on a similar free-weight exercise. In this study, Kraus, Mayhew, Nicholls, Russell, Johnson, Sweeney, & Sloop (1996) compared the number of RTFs completed using a free-weight bench press to the number of RTFs completed using a machine-weight bench press during the YMCA 1-RM prediction test. The authors reported that, on average, significantly more RTFs were performed for the machine-weight bench press (males: 32.2 ± 13.6; females: 29.1 ± 6.8) than for the free-weight bench press (males: 26.6 ± 12.4; females 26.6 ± 8.3). However, these findings require further analysis. In this study, 25 males used a set weight of 36.3 kg for the bench press, while 33 females used a set weight of 15.9 kg. Importantly, the authors reported that the mean 1-RMs for males and females on the machine-weight equipment were 83.5 kg (± 21.2 kg) and

37.0 kg (± 6.2 kg) respectively. Using these results, the 1-RM percentages for males and females can be calculated as 43.5% and 43.0%, respectively. In contrast, the authors reported that the mean 1-RMs for males and females on the free-weight equipment were 71.3 kg (± 19.6 kg) and 33.1 kg (± 5.5 kg), respectively. Using these results the 1-RM percentages for males and females can be calculated as 50.9% and 48.0%, respectively. Therefore, it is possible that the difference in RTFs completed for the machine-weight bench press compared to the free-weight bench press may have been due to the discrepancy in 1-RM percentages used for each exercise. As a consequence, it appears that the results of this study can neither refute nor support the contention that the number of RTFs performed at the same percentage of 1-RM may differ between machine-weight and free-weight exercises. Therefore, it remains unclear whether the accuracy of 1-RM prediction equations might vary if the same exercise was performed using free-weight or machine-weight equipment.

In summary, many of the studies reviewed in this section have demonstrated that the number of RTFs performed at specific percentages of 1-RM can vary significantly across different exercises. Of particular importance in the context of the current investigation are the findings which showed that the number of RTFs performed at the same percentages of 1-RM can differ considerably for the knee extension and leg press exercises. As a consequence, it is possible that the accuracy of 1-RM prediction equations might also differ for these exercises. In addition, while several studies have specifically demonstrated that 1-RM prediction equations can be accurate when used with certain exercises (e.g. bench press, biceps curl, ankle plantarflexion and shoulder internal rotation), other studies have shown that the accuracy of 1-RM prediction equations can vary considerably when used with other exercises (e.g. leg press, hip extension, deadlift, knee extension). Importantly, these studies have generally demonstrated that many 1-RM prediction equations are relatively inaccurate when used with machine-weight leg press and knee extension exercises. However, it is unclear whether these differences in accuracy would be clinically relevant when estimating 1-RM strength, assessing changes in strength or prescribing resistance loads based on estimated 1-RM strength. Finally, it appears that both 1-RM strength and the number of RTFs that can be performed at the same absolute load are greater for machine-weight exercises compared to free-weight exercises, perhaps due in part to a decreased need for concentration, stability and synergistic muscle action.

However, it is less clear whether the number of RTFs performed at the same percentage of 1-RM differ between machine-weight and free-weight exercises. Importantly, the studies by Hoeger, Barette, Hale, & Hopkins (1987) and Hoeger, Hopkins, Barette, & Hale (1990) demonstrated that lifts on a machine-weight bench press at 80% of 1-RM produced a range of RTFs (9.8-12.2), which appears to be similar to the number of RTFs (9.22 ± 2.09) performed on a free-weight bench press in the study by Morales & Sobonya (1996). However, no direct evidence was found in the literature to support or refute the contention that the number of RTFs performed at the same 1-RM percentage varies between free-weight and machine-weight exercises.

2.6.5. Gender

It has been demonstrated that males generally possess significantly greater 1-RM strength than females (Kim et al., 2002; Mayhew, Ball, & Bowen, 1992; Wood et al., 2002). This issue also raises the question of whether males and females might differ in the number of RTFs they can perform at a specific percentage of their 1-RM. If this was the case, then gender could potentially influence the accuracy of 1-RM prediction equations. Importantly, a number of studies have considered this issue. For example, when developing their prediction equation, Mayhew, Ball, Arnold, & Bowen (1992) used a mixed sample of college students consisting of 184 males and 251 females. Using the bench press exercise, each subject was randomly assigned a load corresponding to 55-95% of their 1-RM and asked to perform as many repetitions as possible in one minute. The authors found that while males had significantly greater 1-RM strength than females, the relationships between the percentages of 1-RM and RTFs were described by exponential curves for both males and females and were not significantly different in slope or intercept ($p > 0.05$). Therefore, the authors combined the data for males and females to produce their prediction equation. Importantly, Mayhew, Ball, & Bowen (1992) repeated this study using another sample of college students consisting of 70 males and 101 females. The authors reported that no significant differences were found between males and females for the mean percentage of 1-RM or the mean number of RTFs performed. The authors also reported that the relationships between the percentages of 1-RM and RTFs were fitted by exponential curves in both males and females. Finally, the authors reported that the prediction equation developed by Mayhew, Ball, Arnold & Bowen (1992) adequately described the exponential curves generated in this study. Therefore, based on the results of these two studies, it appears that males and females performed a similar number of RTFs at the same percentages of 1-RM and that a single prediction equation could accurately estimate 1-RM performance for both males and females.

A study by Wood, Maddalozzo, & Harter (2002) has also provided evidence which suggests that 1-RM prediction equations are equally accurate for males and females. In this study the authors assessed the accuracy of seven prediction equations when estimating 1-RM performance in a group of older adults (26 males, 23 females) using 10 weight-machine exercises. The RTFs for each exercise were determined by assigning each subject a percentage of his or her 1-RM, ranging from 50% to 90%. Importantly, the authors analysed the results separately by gender and found that the average percentage of 1-RM randomly assigned to females was the same as, or slightly lower than that assigned to males, except for the shoulder press and low lat pull exercises. In addition, the authors reported that although the average number of RTFs for females was slightly lower than that for males over the full range of RTF trials, in general the average number of RTFs across genders was similar. Finally, with respect to the accuracy of the seven prediction equations, the authors reported that while females exhibited comparable relative accuracy, greater similarity, and lower average error when compared to males over the full range of RTF trials, these gender differences were minimal when RTFs were ≤ 10. Based on these findings, the authors suggested that gender-specific 1-RM prediction equations are unnecessary.

A more recent study by Reynolds, Gordon, & Robergs (2006) has also provided support for the argument that gender does not enhance the accuracy of 1-RM prediction equations. In this study the authors used a sample of 70 subjects (34 males, 36 females) to develop 1-RM prediction equations from RTF tests. Along with other factors, the influence of gender on these equations was evaluated. The authors found that prediction equations based on 5 RTF tests provided the most accurate estimates of 1-RM performance. The authors also reported that the addition of gender to the equations did not significantly improve the accuracy of prediction. Based on these findings, the authors argued that gender may be so interrelated to strength that the 5 RTF data sufficiently accounted for its contribution to the explanation of between-subject variance in 1-RM strength.

Despite the findings described above, it remains unclear whether generic 1-RM prediction equations, other than the Mayhew et al. equation, were developed using data from both male and female subjects. However, based on Mayhew, Ball, Arnold, & Bowen's (1992), Mayhew, Ball, & Bowen's (1992) and Wood, Maddalozzo, & Harter's (2002) findings that females were not significantly different from males with respect to RTFs performed at the same percentage of 1-RM, it would appear that even if these equations were generated from unisex data they could be used for both male and female populations. Certainly the accuracy of a number of prediction equations has been demonstrated using male populations (Mayhew & Mayhew, 2002; Mayhew, Kerksick et al., 2004; Mayhew, Prinster et al., 1995; Mayhew, Ware et al., 1993; Ware et al., 1995; Whisenant et al., 2003), female populations (Cummings & Finn, 1998; Horvat et al., 2003; Wood et al., 2002) and mixed populations (Knutzen et al., 1999; LeSuer et al., 1997; Wood et al., 2002). However, two studies have reported findings that appear to differ from those described above. Akinpelu, Iyaniwura, & Ajagbe (2001) investigated the accuracy of Berger's table when estimating biceps curl 1-RM performance in a group consisting of 50 males and 50 females. Using loads that resulted in RTF ≤ 10, the authors estimated 1-RM strength using Berger's table and compared the results to actual 1-RM performance. The authors then used regression techniques to develop prediction equations that could be used to estimate actual 1-RM performance from the estimated 1-RM values. The authors found that gender specific equations were more accurate when predicting actual 1-RM performance from the estimated 1-RM values generated by Berger's table. Although not specifically discussed by the authors, these findings would seem to suggest that the accuracy of Berger's table was significantly different between males and females when estimating biceps curl 1-RM strength. The reported values for estimated and actual 1-RM performance were 12.23 kg (± 1.85 kg) and 13.24 kg (± 1.56 kg), respectively for males and 6.98 kg (± 1.08 kg) and 7.68 kg (± 0.97 kg), respectively for females. From these results, the mean differences between estimated and actual 1-RM performance can be calculated as 1.01 kg (7.6%) for men and 0.7 kg (9.1%) for women. While this variation in predictive accuracy between males and females appears to be relatively small, it apparently led the authors to ultimately develop gender specific equations.

In another study, Kim, Mayhew, & Peterson (2002) used 37 males and 21 females to develop 1-RM prediction equations based on the YMCA bench press test and found that gender specific equations best predicted 1-RM performance. However, it should be noted that the YMCA bench press test involves lifting a specific weight as many times as possible in 60 seconds and that the weight used differs by gender (36.4 kg for males and 15.9 kg for females). Therefore, it seems likely that gender specific equations were developed because of differences in the absolute loads being used, rather than because of any intrinsic difference between males and females with respect to the number of RTFs they can perform at the same percentages of 1-RM.

In conclusion, it appears that most of the studies described in this section have suggested that gender specific 1-RM prediction equations are unnecessary. In addition, it appears that numerous studies have demonstrated that generic 1-RM prediction equations can produce similar levels of predictive accuracy in both male and female populations.

2.6.6. Age

A knee injury or knee OA could potentially affect an individual at almost any point in their lifespan. Therefore, any assessment of maximal muscle strength used with these pathologies would need to be accurate across a range of ages. Importantly, the accuracy of 1-RM prediction equations has been investigated in a number of different age groups including adolescents, young adults and older adults.

With respect to adolescents, Mayhew, Ball, Arnold, & Bowen (1992) cross-validated the Mayhew et al. equation in two samples of male high school athletes (n = 25) and non-athletes (n = 74). The authors reported that the equation non-significantly overestimated bench press 1-RM performance for both the athletes (1.4% ± 4%) and non-athletes (1.9% ± 8.1%). In addition, the authors reported SEEs of ± 4.1 kg and ± 5.8 kg for the athletes and non-athletes, respectively. Based on these findings, the authors suggested that sub-maximal loads lifted to failure can provide an accurate prediction of 1-RM bench press in adolescent subjects.

In another study involving adolescents, Mayhew, Ware, & Prinster (1993) evaluated the accuracy of four 1-RM prediction equations in a group of 128 male high school students (mean age 16.9 ± 1.0 years). Using the bench press exercise, the authors reported that the Mayhew et al. equation estimated 1-RM performance within an average of 0.32 kg, while the Brzycki, Epley and Lander equations significantly overestimated 1-RM performance by averages of 1.32 kg to 2.13 kg. Based on these results, the authors argued that 1-RM prediction equations provided a safe and accurate method of estimating 1-RM performance in adolescents.

In a study using 47 adolescent male football players (mean age 16.1 ± 0.9 years), Knoll, Cissell, Clemens, Ware, & Mayhew (1995) investigated the accuracy of seven prediction equations when estimating 1-RM bench press performance.. The authors reported that three of the equations produced predicted 1-RM values that were not significantly different from actual 1-RM performance. The Brzycki and Lander equations non-significantly underestimated 1-RM performance by 2.1 lbs and 0.3 lbs respectively, while the Lombardi equation non-significantly overestimated by 1.7 lbs. In addition, the authors reported that the Brzycki and Lander equations both produced 18 players (38%) who had predicted 1-RM values within ± 5 lbs of actual 1-RM performance, while the Lombardi equation produced 23 (49%) players in this range. Based on these findings, the authors suggested that the Lombardi equation accurately predicted 1-RM bench press performance in adolescent football players.

In a more recent study, Kravitz, Akalan, Nowicki, & Kinzey (2003) used 18 adolescent male power-lifters (16.3 ± 1.2 years) to develop 1-RM prediction equations for the squat, bench press and deadlift exercises. The authors reported that the best prediction equations produced SEEs of 5.06 kg for the squat, 2.69 kg for the bench press and 4.97 kg for the deadlift. Based on their findings, the authors suggested that these prediction equations were adequate for estimating 1-RM strength in elite power-lifting adolescents.

Finally, Mayhew, Kerksick, Lentz, Ware, & Mayhew (2004) evaluated the accuracy of ten different prediction equations when estimating 1-RM bench press performance in 213 male high school athletes (16.3 ± 1.1 years). The authors reported that the Brzycki and Lombardi equations non-significantly over-predicted 1-RM performance by an average of 0.8% (± 6.7%) and 0.6% (± 6.4%), respectively. In addition, the authors stated that despite significant under-prediction by approximately 2-3%, the Adams (134/213), Berger (135/213), and O'Conner (136/213) equations produced the most individuals with predicted 1-RM values within ± 4.5 kg of their actual 1-RM performance. Based on these results, the authors suggested that generic prediction equations can be used to accurately estimate 1-RM bench-press performance in the majority of male high school athletes.

A number of studies have also investigated the accuracy of 1-RM prediction equations in young adults. Using 45 college age football players (mean age 20.1 ± 1.5 years), Ware, Clemens, Mayhew, & Johnston (1995) evaluated the accuracy of four prediction equations when used to estimate 1-RM bench press and squat performance. For the bench press, the authors reported that the Mayhew et al. equation significantly underestimated 1-RM performance by an average of 3.1 kg (± 7.7 kg), while the Epley, Lander and Brzycki equations significantly overestimated 1-RM performance by averages of 4.8 kg (± 8.2 kg), 14.1 kg (± 12.0 kg) and 14.2 kg (± 12.4 kg), respectively. For the squat, the authors reported that the Epley, Lander, Mayhew et al. and Brzycki equations all significantly overestimated 1-RM performance by 11.6 kg (± 11.5 kg), 45.7 kg (± 31.2 kg), 48.5 kg (± 14.4 kg) and 47.9 kg (± 33.6 kg), respectively. Based on these findings, the authors suggested that the Epley and Mayhew et al. equations could be used to estimate 1-RM bench press performance in college-age football players, but none of the equations were appropriate for predicting 1-RM squat performance. However, it should be recognized that the testing methods used by the authors in this study resulted in average RTF numbers of 13.9 and 17.4 repetitions for the bench press and squat exercises, respectively, which may have reduced the accuracy of the prediction equations.

Using a group of 65 untrained young adults (males 20.4 ± 3.7 years; females 23.3 ± 6.2 years), LeSuer, McCormick, Mayhew, Wasserstein, & Arnold (1997) assessed the accuracy of seven prediction equations when used to estimate 1-RM performance for the bench press, squat and deadlift exercises. For the bench press, the authors reported that the Mayhew et al. and Wathen equations non-significantly underestimated 1-RM performance by 0.50 kg (0.8%) and 0.54 kg (0.8%) respectively. In addition, the authors reported that the Brzycki, Epley, Lander, Lombardi and O'Conner equations significantly underestimated 1-RM bench press performance by 1 kg to 3.72 kg (1%-6%). For the squat, the authors reported that the Wathen equation non-significantly underestimated 1-RM performance by 2.09 kg (2%). In addition, the authors reported that the other equations significantly underestimated 1-RM squat performance by 3.04 kg to 7.48 kg (3%-8%). Finally, for the deadlift, the authors reported that all of the equations significantly underestimated 1-RM performance by 10.07 kg to 15.29 kg (9%-14%). Based on these findings, the authors suggested that generic prediction equations are appropriate for estimating bench press and squat 1-RM performance but not deadlift 1-RM performance in untrained college students.

In another study using college age football players (mean age 20 ± 1 years), Whisenant, Panton, East, & Broeder (2003) evaluated the accuracy of 11 prediction equations when used to estimate 1-RM performance for the bench press exercise using a fixed load of 102.1 kg. The authors reported that the accuracy of the prediction equations was higher when fewer repetitions were performed. In a subgroup of 31 subjects who performed RTFs ≤ 10, the authors reported that the Brzycki, O'Conner, and Chapman et al. equations significantly underestimated actual 1RM performance by averages of 2.27 kg (± 4.54 kg), 4.54 kg (± 4.99 kg), and 2.27 kg (± 4.54 kg), respectively, while the Mayhew et al. generic equation significantly overestimated actual 1RM performance by an average 2.27 kg (± 4.99 kg). The authors also reported that the Lander, Epley, Wathen, Lombardi, Mayhew et al. NFL-225, and Slovak et al. equations all produced values that did not differ significantly from actual 1-RM values. Based on these findings, the authors suggested that when RTFs ≤ 10 are performed, prediction equations are accurate for estimating 1-RM bench press performance in college-age football players.

Finally, some studies have investigated the accuracy of 1-RM prediction equations in older adults. Knutzen, Brilla, & Caine (1999) assessed the accuracy of six prediction equations when used to estimate 1-RM performance for 11 weight-machine exercises in a group of 51 older adults (mean age 70.7 ± 6.1 years). The authors reported that although the six prediction equations underestimated actual 1RM performance for all of the exercises, the correlations between predicted and actual 1-RM performance demonstrated a moderate to strong relationship for all exercises (upper extremity: $r = 0.77–0.90$; lower extremity: $r = 0.60–0.80$). Based on these findings, the authors suggested that, for older adults, prediction equations can provide a valid measure of 1-RM performance within a range of 1–10 kg, depending on which weight-machine exercise is being performed.

In a more recent study, Wood, Maddalozzo, & Harter (2002) used 49 older adults (mean age 53.55 ± 3.34 years) to evaluate the accuracy of seven prediction equations when used to estimate 1-RM performance for ten weight-machine exercises. The authors reported that both absolute and relative average errors were high for all of the equations, across all of the exercises. However, because of the testing methods used in this study, it should be recognized that many subjects completed RTF numbers > 10. Importantly, when the authors analysed the subjects who performed RTFs ≤ 10 separately, they found that the relative accuracy, similarity, and average error of the prediction equations improved significantly. The authors also reported that the Mayhew et al., Epley, and Wathen equations demonstrated the highest relative accuracy and lowest average error across the range of exercises used in this study. However, based on the relatively high average errors produced for all of the equations across all of the exercises in this study, the authors suggested that the practical application of these equations in older adults may be limited in some respects.

Finally, Kemmler, Lauber, Wassermann, & Mayhew (2006) used 70 resistance trained postmenopausal women (age 57.4 ± 3.1 years) to investigate the accuracy of eight prediction equations when estimating 1-RM performance for four machine-weight exercises, over a wide range of RTFs (3-20 RTFs). The authors reported that an equation they developed (KLW equation) accurately predicted 1-RM performance for all of the exercises, with mean absolute differences between actual 1-RM and predicted 1-RM of 1.5–3.1% and with coefficients of variation of ≤ 3.3%. In addition, the authors reported that the O'Connor equation produced comparable results with mean absolute differences between actual 1-RM and predicted 1-RM of 1.6–3.5% (except for the 3-6 RTF leg press = 6.2%). The authors argued that these findings support the contention that prediction equations can adequately estimate 1-RM performance across different exercises in trained, older female subjects. However, it should be noted that the Brzycki, Epley, Lander, Lombardi, Mayhew et al. and Wathen equations were not accurate when predicting 1-RM performance for these exercises over the full range of RTFs (range of mean absolute differences between actual 1-RM and predicted 1-RM: 1.8–32.1%). Nonetheless, the predictive accuracy of these equations was generally superior for the 3-5 and 6-10 RTF ranges (mean absolute differences: 1.9-12.2%), compared to the 11-15 and 16-20 RTF ranges (mean absolute differences: 1.8-32.1%).

In conclusion, it appears that when individuals perform RTFs ≤ 10, generic prediction equations can generally provide accurate estimates of 1-RM performance across a range of age groups, spanning adolescents to older adults.

2.6.7. Anthropometric Variables

The results of previous research studies have indicated that maximal strength may be related to anthropometric variables such as height, body mass, body-fat percentage, limb circumference and limb CSA (Mayhew, Ball, Ward, Hart, & Arnold, 1991; Mayhew, McCormick, Piper, Kurth, & Arnold, 1993; Mayhew, Piper, & Ware, 1993). However, it should be noted that some studies have demonstrated that the correlations between structural dimensions and strength are weaker for females compared to males and for lower extremity exercises compared to upper extremity exercises (Mayhew & Hafertepe, 1996; Mayhew, Piper et al., 1993; Scanlan, Ballmann, Mayhew, & Lantz, 1999). Nevertheless, a number of authors have investigated whether the addition of anthropometric variables can improve the accuracy of 1-RM prediction equations (Cummings & Finn, 1998; Horvat et al., 2003; Kim et al., 2002; Kravitz et al., 2003; Mayhew, Jacques et al., 2004; Mayhew, Kerksick et al., 2004; Reynolds et al., 2006; Rose & Ball, 1992; Whisenant et al., 2003).

Some studies have suggested that anthropometric variables can add to the accuracy of 1-RM prediction equations. Rose & Ball (1992) investigated the YMCA bench press test in a group of 84 untrained college women and found that bench press absolute endurance along with body weight was slightly more effective for predicting bench press 1-RM performance (SEE = 3.27 kg using a 15.9 kg load; SEE = 2.95 kg using a 20.4 kg load), than absolute endurance alone (SEE = 3.34 kg using a 15.9 kg load; SEE = 3.14 kg using a 20.4 kg load).

In another study, Ball, Mayhew and Bowen (1995) assessed whether parallel dips to failure could predict 1-RM bench press strength in 246 men. The authors found that although dips to failure were related to 1-RM strength ($r = 0.49$), they were inadequate for predicting maximal strength (SEE = 17.3 kg). However, the authors reported that the addition of body mass to the prediction equation resulted in improved accuracy (r = 0.82, SEE = 11.5 kg), although the further addition of arm CSA increased predictive accuracy by only a small degree (r = 0.84, SEE = 10.9 kg).

In a more recent study, Horvat et al. (2003) conducted a study to develop an equation capable of accurately predicting bench press 1-RM performance in 65 female athletes. The authors found that RTFs with a 25 kg load (r = 0.866), RTFs with a 31.8 kg load (r = 0.909) and lean body mass (r = 0.445) were the best predictors of 1-RM strength. The authors also reported that predicting bench press 1-RM performance with a one-variable model using RTFs at 31.8 kg yielded an adjusted R^2 value of 0.815, whereas a two-variable model using RTFs at 31.8 kg and lean body mass produced an adjusted R^2 value of 0.832. Based on these results, the authors concluded that the one-variable model might be adequate for predicting a 1-RM bench press in this population. However, the authors ultimately suggested that the anthropometric variable of lean body mass should be included in the equation for optimal accuracy.

As part of their study, Whisenant, Panton, East, & Broeder (2003) measured the demographic variables of race, age, height, weight, fat-free weight and percent body fat in order to determine whether these factors increased the accuracy of 11 1-RM prediction equations. Using a group of 69 collegiate football players, the authors reported that the demographic variables increased the explained variance by less than 2% for eight of the equations (Chapman et al. = 1.7%, Epley = 1.7%, Epley and Mayhew combo =1.5%, Mayhew et al. NFL-225 lb = 1.1%, Mayhew et al. = 1.7%, O'Conner = 1.7%, Slovak et al. = 1.7%, and Wathen = 0.9%). In contrast, the demographic variables increased the explained variance in the Brzycki, Lander, and Lombardi equations by 11.2%, 10.7% and 5.1%, respectively. Based on these findings, the authors suggested that demographic variables should be included when utilizing the Brzycki, Lander, and Lombardi equations.

Finally, while investigating the accuracy of 1-RM prediction equations in 213 male high school athletes, Mayhew et al. (2004) also evaluated the influence of a number of anthropometric variables including age, height, weight and body mass index (BMI). The authors reported that for a group of subjects in which the prediction equations overestimated 1-RM performance, none of the anthropometric variables were significantly correlated with the degree of over prediction (r = –.09 to .27, n = 45). However, for a group of subjects in which the prediction equations underestimated 1-

RM performance, body weight was significantly correlated with the degree of under prediction ($r = -.36$, $n = 35$). In addition, BMI was significantly correlated with the degree of prediction error in both the over predicted ($r = .37$) and under predicted groups ($r = -.46$). Based on these findings, the authors argued that when body weight was higher for a given height there was a greater tendency to over predict 1-RM performance. In contrast, when body weight was lower for a given height there was a greater tendency to under predict 1-RM performance. However, despite these findings, the authors did not specifically suggest that anthropometric measures should be added to 1-RM prediction equations.

In contrast to studies described above, a number of investigations have provided evidence that anthropometric variables do not improve the precision of 1-RM prediction equations. As part of their study, Cummings & Finn (1998) used regression analysis to develop equations for estimating maximal bench press performance using the relationship between 1-RM bench press strength and a number of performance and/or anthropometric variables in a group of 57 untrained women. A forward stepwise regression analysis selected three variables to be incorporated into the prediction equations including the weight lifted, the number of RTFs completed and the anthropometric variable of biacromial breadth. The authors found that an equation consisting of RTFs and the weight lifted produced the best predictive accuracy (SEE = 0.728 kg). In contrast, the addition of biacromial breadth to the equation actually reduced the predictive accuracy (SEE = 1.672 kg). Importantly, the authors suggested that measurement error related to biacromial breadth might explain this loss of accuracy. Finally, the authors reported that a stepwise analysis using only anthropometric variables as predictors lead to an equation incorporating upper arm circumference. However, this equation proved to be the least accurate of any evaluated in the study ($r = 0.47$, SEE = 2.34 kg). Based on these findings, Cummings & Finn (1998) suggested that the addition of anthropometric variables to 1-RM prediction equations was not appropriate and might actually introduce another source of measurement error that could affect the accuracy of these equations.

In a study designed to evaluate the effect of cadence on the YMCA bench press test, Kim, Mayhew, & Peterson (2002) also assessed the impact of a number of anthropometric variables including age, height, weight, fat-free mass, and body fat percentage. The authors found that although the number of repetitions completed at cadences of 30 and 60 reps per minute correlated well with 1-RM bench press performance, the addition of anthropometric variables did not enhance the predictive accuracy of the equations.

A study by Kravitz, Akalan, Nowicki, & Kinzey (2003) investigated the correlation between 1-RM performance in 18 elite male high school powerlifters and a number of anthropometric variables including height, weight, chest circumference and biceps circumference. The authors found that none of the anthropometric variables were significantly correlated with 1-RM strength for the squat, bench press or deadlift exercises performed in this study. Interestingly, the authors suggested that the anthropometric variables might have had a lesser effect on 1-RM strength in these highly trained subjects because their advanced lifting techniques could have compensated for any differences in body dimensions.

More recently, Mayhew et al (2004) conducted a study to investigate whether anthropometric variables increased the accuracy of the NFL-225 lb test when predicting 1-RM bench press performance in 61 college football players. The authors found that the addition of anthropometric variables including body fat percentage, lean body mass, and arm CSA did not improve the predictive accuracy of the NFL-225 lb test. In addition, the authors reported that the anthropometric variables could not explain why 1-RM performance was significantly over-predicted or under-predicted in some subjects. In an attempt to clarify why the anthropometric variables did not enhance the accuracy of the NFL-225 lb test the authors suggested that since muscle hypertrophy may not always elicit proportional increases in maximal strength, the resistance training program used by the subjects in this population may have enhanced muscle size to a greater degree than it developed strength.

Finally, in a study designed to develop regression equations capable of predicting 1-RM bench press and leg press performance in 70 subjects of varying ages, Reynolds, Gordon, & Robergs (2006) also assessed the influence of a number of anthropometric variables including height, weight, fat-free mass, body fat percentage, arm girth, chest girth and thigh girth. The authors reported that the most accurate predictions of strength were derived from 5-RTF tests and that the addition of anthropometric variables did not significantly improve the predictive accuracy of these equations.

Based on these findings, the authors argued that anthropometric variables may be so interrelated to strength that the 5-RM data sufficiently accounted for their contribution to the explanation of between-subject variance in 1-RM strength.

In conclusion, it appears some studies have found that the addition of anthropometric variables can slightly improve the accuracy of 1-RM prediction equations. However, many other studies have demonstrated that RTFs and load are the key variables for predicting maximal muscle strength, with anthropometric measures providing no additional improvement in accuracy. Considering the extra time that would be required to collect anthropometric measurements and the risk of measurement errors, the addition of anthropometric variables to 1-RM prediction equations in clinical settings does not appear to be appropriate.

2.6.8. Summary

Literature relating directly and indirectly to the accuracy of eleven generic 1-RM prediction equations was reviewed in this section. Seven of these equations have been investigated repeatedly (Brzycki, Epley, Landers, Lombardi, Mayhew et al., O'Connor and Wathen), while the Adams, Berger, Brown and KLW equations have been studied less frequently. However, no single equation was consistently identified as the best predictor of 1-RM performance. Errors of 5% to 10% between predicted and actual 1-RM performance were commonly reported, although errors ≤ 3% and ≥ 20% were also reported. A number of variables that could potentially influence the accuracy of 1-RM prediction equations were also reviewed in this section. These included the load lifted, the number of RTFs performed, the speed at which RTFs were performed, the equipment and exercises used, and the training status, gender, age and anthropometric characteristics of the individuals being tested. With respect to load and RTFs, it was generally demonstrated that predictive accuracy was greater with loads which produced RTFs ≤ 10 (typically > 75% of 1-RM). With respect to repetition speed, a single study provided evidence that faster lifting cadences might be more appropriate for RTF testing (e.g. a one second concentric phase and a one second eccentric phase). With respect to the exercises and equipment used, several studies demonstrated that predictive accuracy was good with some exercises (e.g. bench press, biceps curl, ankle plantarflexion and shoulder internal rotation), but not with others (e.g. leg press, hip extension, deadlift, knee extension). With respect to training status, a number of studies provided evidence which suggested that predictive accuracy might differ between resistance trained and untrained individuals, although the findings were equivocal. With respect to gender, age and anthropometric characteristics, the majority of studies reported that these variables did not have any significant impact on the accuracy of generic 1-RM prediction equations. Finally, while many studies acknowledged that errors between predicted and actual 1-RM performance are not uncommon, it was generally suggested that the use of generic prediction equations is appropriate when actual 1-RM testing is contraindicated.

2.7. LITERATURE REVIEW SUMMARY

Knee injuries and knee OA are common musculoskeletal pathologies. Although numerous detrimental outcomes have been identified following knee injuries and the onset of knee OA, it appears that one of the most consistent features associated with these disorders is the development of significant quadriceps femoris muscle weakness. Importantly, quadriceps weakness could potentially moderate an individual's prospects of returning to their previous level of physical activity and might even be a risk factor for the development of further acute injuries and/or ongoing degenerative changes in the knee joint. Therefore, it seems likely that maximal strength testing and resistance training would be critical components of any rehabilitation programme aimed at addressing these issues.

An accurate evaluation of maximal muscle strength may be valuable for a number of reasons. Firstly, it can facilitate the objective identification and quantification of baseline strength deficits. Secondly, measures of maximal strength can be used to calculate appropriate training loads for resistance exercise programmes. Thirdly, regular strength evaluations allow changes in strength to be monitored objectively and can therefore provide a means of determining when alterations in a training programme might be required. Finally, evaluations of maximal strength can be used for discharge planning and may assist in determining when a return to functional and/or sporting activities is appropriate.

The gold standard method for measuring maximal isoinertial strength is the 1-RM test. However, because 1-RM testing is time consuming and might be considered inappropriate for some individuals, a number of generic equations have been developed to allow the prediction of 1-RM performance from sub-maximal loads. Some studies have demonstrated that these generic 1-RM prediction equations can produce acceptable levels of accuracy in healthy populations and in individuals with plantarflexor unit injuries. However, despite the reported use of 1-RM prediction equations in injured populations, the accuracy of these techniques has yet to be investigated in individuals with joint pathologies. If any of these equations were found to be accurate in subjects with knee injuries or knee OA, they might provide health professionals with a more efficient, and perhaps safer, alternative to 1-RM testing in these populations.

3. CHAPTER 3: MATERIALS AND METHODS

3.1. INTRODUCTION

This chapter details the materials and methods that were used to perform this study. The first section describes the study design, while the second section outlines the subject recruitment methods and the inclusion and exclusion criteria. The third section reviews the testing equipment and the fourth section describes the testing procedures. The fifth section summarizes the 1-RM prediction equations evaluated in this study, while the final section presents the statistical procedures used to analyse the data.

3.2. DESIGN

This investigation was a descriptive quantitative research study utilizing a cross-sectional design. The variables collected were:

1. Demographic variables including age, gender, height and weight.
2. Clinical details including date and type of injury for the knee injury subjects and functional activity level for the knee OA subjects which was collected using the Western Ontario and MacMaster Universities (WOMAC) OA index.
3. Each subject's unilateral 1-RMs for the leg press and knee extension exercises.
4. The number of unilateral RTFs that each subject could perform for each exercise using sub-maximal loads. These variables were then entered into eleven 1-RM prediction equations and the Poliquin chart in order to calculate the predicted unilateral 1-RMs for each subject.

3.3. SELECTION OF SUBJECTS

Based on the findings of Lovelace (2005), a 5 percent difference between the predicted and actual 1RM score was deemed as notable. The number of subjects needed was then calculated on this basis, with the alpha level set at 0.05 and the beta level at 0.8. The results showed that 20 subjects would be required for the current study. Subjects were invited to participate in the study through advertising and word of mouth from local physiotherapy clinics, the Auckland University of Technology and the general population. Inclusion criteria for subjects with knee OA were a diagnosis based on a Kellgren-Lawrence (1957) x-ray score of 2 or more (Appendix 1) and/or the Altman (1991) clinical classification criteria (Appendix 2). Inclusion criteria for subjects with knee injuries were a significant injury to the knee (ligament injuries and/or meniscal injuries) which interfered with function and required a period of non-weightbearing and subsequent rehabilitation with a health professional. This broad range of injuries was chosen to increase the external validity of the results. Diagnosis of the injury was confirmed through evaluation by the researcher, who is a registered physiotherapist with post-graduate training in musculoskeletal physiotherapy. Subjects who had undergone surgery for knee ligament and/or meniscus injuries were also included in the study. Subjects were asked to provide medical records describing their surgical intervention, if available. Where this was not possible, subject recollection was relied upon with respect to the surgical interventions that were performed. This was deemed acceptable because individuals should be able to accurately recall an event of such magnitude. Exclusion criteria for subjects with significant knee injuries included injury and/or surgical repair within the past three months. In addition, subjects who underwent surgery were excluded if they had not received clearance from their surgeons to return to unrestricted activity. Exclusion criteria for all subjects included a significant history of pathology, joint disorder, injury or pain affecting the trunk or lower-limbs (other than the knee joint) that might influence the tests undertaken. Finally, subjects were excluded from the study if 1) they had a systemic arthritic condition such as rheumatoid arthritis; 2) they had undergone total knee arthroplasty; 3) they had any medical conditions that would have precluded them from applying maximal physical effort such as hypertension, cardiovascular disease, cerebrovascular disease or significant osteoporosis.

Written and verbal explanations of the procedures involved in this study and an opportunity to ask questions about the study were provided to all subjects prior to testing (Appendix 3). Translation services for the written and verbal explanations were available if required. Each subject's personal and medical information was coded to prevent the identification of individual results.

Ethical approval for this study was received from the Auckland University of Technology Ethics Committee on 13 July 2006, reference number 06/110 (Appendix 4) and all subjects signed a document of informed consent (Appendix 5).

3.4. EQUIPMENT

A seated knee extension machine and a seated leg press machine were used for the strength testing procedures. This type of equipment is frequently used for knee rehabilitation and quadriceps muscle strengthening. The seated knee extension machine (Fitness Works) provided resistance in 6 kg increments from 6 kg to 96 kg. For weights above 96 kg, additional 1.1 kg or 2.2 kg plates and/or dumbbells of varying weights were added to the weight-stack. All additional weights were weighed using the EKS calibrated scales to ensure the weight markings were accurate. The back rest was adjusted so that the axis of the knee joint was aligned with the axis of the resistance arm. The footpad was positioned at approximately 2.5 cm proximal to the lateral malleolus. The starting and ending position for the seated knee extension exercise was approximately 90º of knee flexion. From the starting position, each subject extended the knee until full available knee extension was reached and then returned to the starting position.

The seated leg press machine (Fitness Works) provided resistance in 10 kg increments from 6 kg to 206 kg. Additional weight increments were added as needed using 1.1 kg or 2.2 kg plates. The back rest was adjusted to an angle of 70º. Each subject's foot was placed with the heel at the bottom of the foot plate. The hip, knee and ankle joints were aligned so that the knee moved in a line intersecting with the second toe. The starting and ending position for the seated leg press exercise was approximately 90º of knee flexion. From the starting position, each subject straightened the leg until full available knee extension was reached and then returned to the starting position.

An upright stationary bike (True Z8) was used as part of the warm up procedure. Height was measured with a steel tape measure (Surgical and Medical Products) secured above the subject at a height of two meters. Body mass was measured with a calibrated EKS electronic scale.

3.5. QUESTIONNAIRES

A questionnaire devised specifically for this study was used to collect clinical details including date and type of injury from the knee injury subjects (see Appendix 6).

The WOMAC index was used for subjects with knee OA (Version VA3.1). This index is self administered and can be used to subjectively assess pain, disability and joint stiffness in subjects with knee and hip OA. Its validity, responsiveness and reliability have been supported in numerous studies (Bellamy, Buchanan, Goldsmith, Campbell, & Stitt, 1988; Davies, Watson, & Bellamy, 1999). The index consists of a battery of 24 questions and, in the current study, utilized visual analogue scales which combined to produce a maximum value of 240 (see Appendix 7).

3.6. PROCEDURES

All procedures were performed at the Auckland University of Technology Fitness Centre, Akoranga campus. The testing procedures were divided into three sessions: 1) a familiarization session; 2) a 1-RM testing session; and 3) a repetitions to failure testing session, the results of which were used to calculate predicted 1-RM. The three sessions were separated by a minimum of two and a maximum of fourteen days to minimize the risk of delayed onset muscle soreness.

3.6.1. Standardized Warm-Up

Subjects performed five minutes of cycling on a stationary bike at a low level of resistance, followed by two 20 second static stretches for the quadriceps muscles. Subjects then performed a set of unilateral knee extensions using a light resistance that allowed 8-12 repetitions. Subjects then rested for three minutes before performing a second set of unilateral knee extensions using a light resistance that allowed 6-8 repetitions. Subjects then rested for a further three minutes.

3.6.2. Familiarization Session

During the familiarization session the demographic variables of age, gender, height and weight were collected. In addition, the subjects with knee OA completed the WOMAC index, while the subjects with knee injuries completed the questionnaire regarding their date of injury and type of injury. Subjects then performed the standardized warm-up before being familiarized with the knee extension procedures, followed by the leg press procedures. During the familiarization process verbal instructions and feedback were provided regarding lifting technique and lifting cadence. A lifting cadence consisting of a one second concentric phase and a one second eccentric phase was selected for the testing procedures based on the work of Sakamoto & Sinclair (2006). The weights were fully lowered between each repetition and subjects were instructed to avoid excessive trunk movements during the exercises. Subjects were also instructed to keep their heel on the foot plate during the leg press exercise to limit activation of the calf muscles. Finally, all tests were performed unilaterally to allow comparisons between the involved and uninvolved limbs.

The 1-RM testing procedure was based on a protocol described by Baechle, Earle & Wathen (2000). Initially a load was selected that the subject lifted for 2 to 5 repetitions. Following a three minute rest period the load was increased by ≈5-15% and a 1-RM was attempted. If the subject completed one repetition they stopped and rested for three minutes. Then, depending on the subject's perceived level of exertion, the load was increased by a further 5-15% and the 1-RM test was repeated. This process continued until the maximum load that the subject could lift with proper technique for only one repetition was reached. If at any point the subject was unable to complete one full repetition, the load was decreased by ≈5-10% until a successful lift was completed. For the familiarization process, a maximum of five 1-RM lifts were performed. The heaviest load lifted during this process was recorded and used as the starting resistance during the actual 1-RM testing session.

For the predicted 1-RM test, a load was selected that the subject believed they could lift for 10 repetitions or less. If a subject was able to perform more than ten repetitions with this load they stopped and rested for three minutes. Then, depending on the subjects perceived level of exertion, the load was increased by ≈10-20% and the test was repeated. When required, this process was continued until a load was reached that restricted the subject to ten repetitions or less.

Following the familiarization session a coin toss was conducted to determine the order in which the testing procedures would be performed during the subsequent sessions.

3.6.3. 1-RM Testing Procedure

Following the warm up procedure each subject attempted a 1-RM lift on the seated knee extension machine using 90% of the 1-RM load they recorded during the familiarization session. If the subject completed one repetition they stopped and rested for three minutes. Then, depending on the subjects perceived level of exertion, the load was increased by a further ≈5-15% and the 1-RM test was repeated. This process continued until the maximum load that the subject could lift with proper technique for only one repetition was reached. If at any point the load was too heavy for the subject to complete one full repetition, the load was decreased by ≈5-10% until a successful lift was completed. This procedure was then repeated for the leg press exercise.

3.6.4. Predicted 1-RM Testing Procedure

Following the warm-up procedure a load was selected on the seated knee extension machine which each subject believed they could lift for 10 repetitions or less. If the subject performed ≤10 repetitions the results were recorded. If a subject was able to perform more than ten repetitions they stopped and rested for three minutes. Then, depending on the subjects perceived level of exertion, the load was increased by ≈10-20% and the test was repeated. If required, this process continued until a load was reached that restricted the subject to ten repetitions or less. Any repetitions that involved excessive trunk movement or did not achieve full ROM were not counted. This procedure was then repeated for the leg press exercise.

3.7. 1-RM PREDICTION EQUATIONS

Eleven 1-RM prediction equations were selected from the literature to be used in this study (Table 3.1). The Poliquin chart was also investigated because it is utilized in some physiotherapy practices and fitness centres (Table 3.2). The predicted 1-RM was compared to the actual 1-RM for both the injured and control limbs.

Table 3.1: 1-RM Prediction Equations

Prediction Equation	Formula
Adams[1]	$1\text{-RM} = W/(1-0.02*R)$
Berger[1]	$1\text{-RM} = W/(1.0261\ e^{-0.0262*R})$
Brown[1]	$1\text{-RM} = (R*0.0328 + 0.9849)*W$
Brzycki[1]	$1\text{-RM} = W/(1.0278-0.0278*R)$
Epley or Welday[1]	$1\text{-RM} = (0.033*R*W) + W$
KLW[2]	$1\text{-RM} = W*(0.988–(0.0000584*R^3 + 0.00190*R^2\ 0.0104*R))$
Lander[1]	$1\text{-RM} = W/(1.013-0.0267123*R)$
Lombardi[1]	$1\text{-RM} = R^{0.1}*W$
Mayhew et al.[1]	$1\text{-RM} = W/(0.522 + 0.419e^{-0.055*R})$
O'Connor et al.[1]	$1\text{-RM} = 0.025*(W*R) + W$
Wathen[1]	$1\text{-RM} = W/(0.488 + 0.538e^{-0.075*R})$

R = repetitions to failure; W = weight used for repetitions to failure.
[1]Mayhew, Kerksick, Lentz, Ware, & Mayhew (2004),
[2]Kemmler, Lauber, Wassermann & Mayhew (2006)

Table 3.2: Poliquin Chart

Repetitions to Failure	% of 1-RM
1	100
2	94.3
3	90.6
4	88.1
5	85.6
6	83.1
7	80.7
8	78.6
9	76.5
10	74.4

Reported in Lovelace (2005)

3.8. STATISTICAL ANALYSES

The primary purpose of this study was to determine whether estimated 1-RM performance calculated from one or more prediction equations agreed sufficiently with actual 1-RM strength to allow the equation(s) to be used in clinical situations with confidence. Therefore, the following statistics were used to assess the level of agreement between the predicted 1-RM values and actual 1-RM values for the knee extension and leg press exercises.

SPSS for Windows Version II and Microsoft Office Excel 2003 were used for the data analyses. Descriptive statistics were calculated for the dependent variables and the data were checked for normality. Paired t-tests were used to determine whether actual 1-RM values were significantly different across the control and affected limbs. In addition, paired t-tests were conducted using the percentage difference scores ((predicted 1-RM - actual 1-RM) / actual 1-RM) from both limbs in order to ascertain whether there were any significant differences in the predictive accuracy of each equation across the control and affected limbs. Alpha levels for these inferential tests were set at 0.05. Bland and Altman graphs and level of agreement calculations were used to gain an appreciation of the distribution of error between the actual 1-RM and the predicted 1-RM data. These analyses included measures of bias and 95% limits of agreement (LOA). The 95% LOA represented the range within which test-retest difference scores fell 95% of the time (Hopkins, 2000). Intraclass correlation coefficients between the actual 1-RM and predicted 1-RM data were also calculated using a two way fixed model with the mode of assessment (actual 1-RM or predicted 1-RM) as the fixed variable and the subject as the random variable (Muller & Buttner, 1994). Although intraclass correlation coefficients do not provide evidence about the level of agreement between predicted and actual 1-RM performance, they can provide information about the relative reliability of measurement techniques (Atkinson & Nevill, 1998).

Typical error, typical error as a coefficient of variation and the total error of measurement were calculated using an Excel spreadsheet developed by Hopkins (2007b). The accuracy of this spreadsheet was manually verified by the researcher. Typical error is a measure of within subject standard deviation and represents the random variability of an individual's scores across trials (Hopkins, 2000). Typical error can be calculated by dividing the standard deviation of the difference scores between predicted and actual 1-RM performance by the square root of two (Hopkins, 2007a). Typical error as a coefficient of variation represents the typical error expressed as a percentage of the mean score. Typical error as a coefficient of variation (CV) can be calculated using the formula %CV = $100*(e^{s/100}-1)$, where s is the typical error of the 100 log transformed difference scores (Hopkins, 2007a). The total error of measurement (total error) is a form of typical error affected by a change in the mean across trials (Hopkins, 2007a). Therefore, in conjunction with typical error, this value may give an indication of the error due to a change in the mean across the trials. Total error can be calculated by determining the average of the variance of the 100 log transformed difference scores and then taking the square root of this value. Total error (TE) can then be expressed as a percentage using the formula %TE = $100*(e^{TE/100}-1)$ (Hopkins, 2007a).

Finally, the number of subjects with predicted 1-RM values within 5% or less of their actual 1-RM values was determined for each equation.

4. CHAPTER 4: RESULTS

4.1. INTRODUCTION

This chapter is divided into two main sections. The first section describes the subject's demographic information, knee injury or knee OA characteristics and resistance training status. The second section is divided into two sub-sections representing the knee injury and knee OA groups. The degree of conformity between actual and predicted 1-RM performance for the knee extension and leg press exercises is described for both groups.

4.2. DEMOGRAPHICS

Fifty subjects volunteered to participate in this study. Twenty five subjects had knee injuries. Five of these subjects were excluded prior to testing. Two subjects became pregnant, one subject had a family emergency, one subject was less than three months post-ACL reconstruction and one subject decided she was too busy to participate. The remaining group of 20 subjects included 14 males and 6 females. All 20 subjects were able to complete testing on the knee extension machine, although some ACL deficient subjects complained of feelings of apprehension and/or instability. One subject could not perform the leg press exercise because of a groin strain. Therefore, 19 subjects with knee injuries performed the leg press testing procedure.

Twenty five subjects had knee OA. Six subjects were excluded prior to testing and one subject was excluded during testing. Three of these subjects had systemic arthritic conditions, one subject underwent total knee arthroplasty, one subject developed lower extremity cellulitis and one subject decided she was too busy to participate. In addition, one subject was withdrawn from the study after experiencing patellar tendon pain and swelling of the knee following the familiarization session. The remaining group of 18 subjects included 7 males and 11 females. During the leg press exercise ten subjects complained of crepitus and/or mild knee discomfort, although all 18 subjects were able to complete the testing procedures. However, six subjects (1 male, 5 females) could not perform the knee extension exercise due to severe anterior knee pain. Therefore, 12 knee OA subjects completed the knee extension testing procedure. The knee injury group was significantly different from the OA group with respect to age but not height or body mass. Table 4.1 presents the demographic data for these groups, while Table 4.2 displays the characteristics of the knee injury subjects.

Table 4.1: Demographic Data

	Mean	SD	Range
Subjects with Knee Injuries			
Age (years)	33.2	9.9	20-54
Height (meters)	1.8	0.1	1.5-1.9
Mass (kg)	75.9	11.9	55.4-100.2
BMI (kg/m^2)	24.6	2.3	20.4-29.0
Subjects with Knee OA			
Age (years)	57.4	10.0	36-76
Height (meters)	1.7	0.1	1.6-1.9
Mass (kg)	78.4	13.2	59.6-101.9
BMI (kg/m^2)	26.6	4.0	19.1-34.6

SD = standard deviation; BMI = body mass index

Table 4.2: Knee OA and Knee Injury Characteristics

Knee Injury Characteristics	
Time since injury (mean ± SD / range)	81.0 ± 89.4 mths / (6-300 mths)
Isolated ACL injury	5/20 subjects
Isolated PCL injury	2/20 subjects
Isolated medial meniscus injury	4/20 subjects
Isolated lateral meniscus injury	4/20 subjects
Combined ACL / meniscus injury	5/20 subjects
Surgical intervention for above injuries	12/20 subjects
Resistance trained	7/20 subjects
Hx of unilateral lower extremity training	3/20 subjects

All of the knee injured subjects sustained their injuries while participating in sporting or recreational activities. Seven subjects sustained isolated ligament injuries and, of these, three underwent surgery. Eight subjects sustained isolated meniscal injuries and. of these, four underwent surgery. Five subjects sustained combined ligament and meniscal injuries and all of these subjects underwent surgery. Of the 20 knee injured subjects, seven were classified as resistance trained (defined as resistance training of greater than three months duration at the time of testing).

The mean WOMAC score for the knee OA group was 28.1 out of 240. In addition, five of the 18 knee OA subjects were categorised as resistance trained.

4.3. COMPARISON OF PREDICTED & ACTUAL 1-RM DATA

The level of agreement between predicted and actual 1-RM performance for the knee extension and leg press exercises was established using typical error, the total error of measurement, ICCs, Bland and Altman limits of agreement and by assessing the number of subjects with predicted 1-RM values within 5% or less of their actual 1-RM values. The results are presented below for the knee injury and knee OA subjects.

4.3.1. Knee Injured Subjects

4.3.1.1. Knee Extension for Knee Injured Subjects

The mean group values for predicted and actual knee extension 1-RM performance are displayed in Table 4.3. The mean values for actual knee extension 1-RM performance were 100.4 kg (SD 36.6) for the affected limbs and 107.9 kg (SD 34.7) for the control limbs. These values were significantly different ($p < 0.05$). The predicted knee extension 1-RM values for the affected limbs ranged from 91.2 kg (33.2 SD) for the KLW equation to 100.2 kg (36.3 SD) for the Wathen equation. The predicted 1-RM values for the control limbs ranged from 96.0 kg (30.8 SD) for the KLW equation to 105.3 kg (33.8 SD) for the Wathen equation. The results of the paired t-tests using the percentage difference scores ((predicted 1-RM – actual 1-RM) / actual 1-RM) demonstrated that there were no significant differences in predictive accuracy across the control and affected limbs for the Adams, Berger, Brown, Epley, KLW, Lombardi, Mayhew et al., O'Connor and Poliquin prediction methods.

However, significant differences in predictive accuracy across the control and affected limbs were found for the Brzycki (p = 0.039) and Lander (p = 0.041) equations. In addition, the difference in the predictive accuracy across the control and affected limbs approached statistical significance for the Wathen equation (p = 0.057). All three of these equations produced greater mean underestimations of 1-RM performance in the control limbs compared to the affected limbs.

Table 4.3: Knee Extension Actual and Predicted 1-RM Results

1-RM Method	Affected Limb Maximal Strength in kg (mean ± SD)	Control Limb Maximal Strength in kg (mean ± SD)
Actual 1-RM	100.4 ± 36.6	107.9 ± 34.7
Adams	93.3 ± 34.0	98.3 ± 31.5
Berger	94.3 ± 34.2	99.2 ± 31.8
Brown	97.8 ± 35.5	102.9 ± 33.0
Brzycki	97.8 ± 35.1	102.7 ± 33.0
Epley	99.1 ± 36.0	104.3 ± 33.5
KLW	91.2 ± 33.2	96.0 ± 30.8
Lander	98.5 ± 35.4	103.5 ± 33.2
Lombardi	95.9 ± 35.6	101.4 ± 32.5
Mayhew et al.	98.7 ± 36.3	104.1 ± 33.4
O'Connor	93.9 ± 34.4	99.0 ± 31.7
Poliquin	99.9 ± 36.2	105.1 ± 33.7
Wathen	100.2 ± 36.3	105.3 ± 33.8

Bland and Altman graphs were plotted to give an appreciation of the bias for each of the prediction methods (see Figures 4.1 and 4.2). These graphs plot the differences between actual and predicted 1-RM values for an individual against the mean value of actual and predicted 1-RM performance for that individual (Bland & Altman, 1986). The bias, limits of agreement, ICCs, typical errors, typical errors as coefficients of variation (COVs), total errors of measurement and numbers of subjects within 5% or less of their true 1-RM are shown in Tables 4.4 and 4.5.

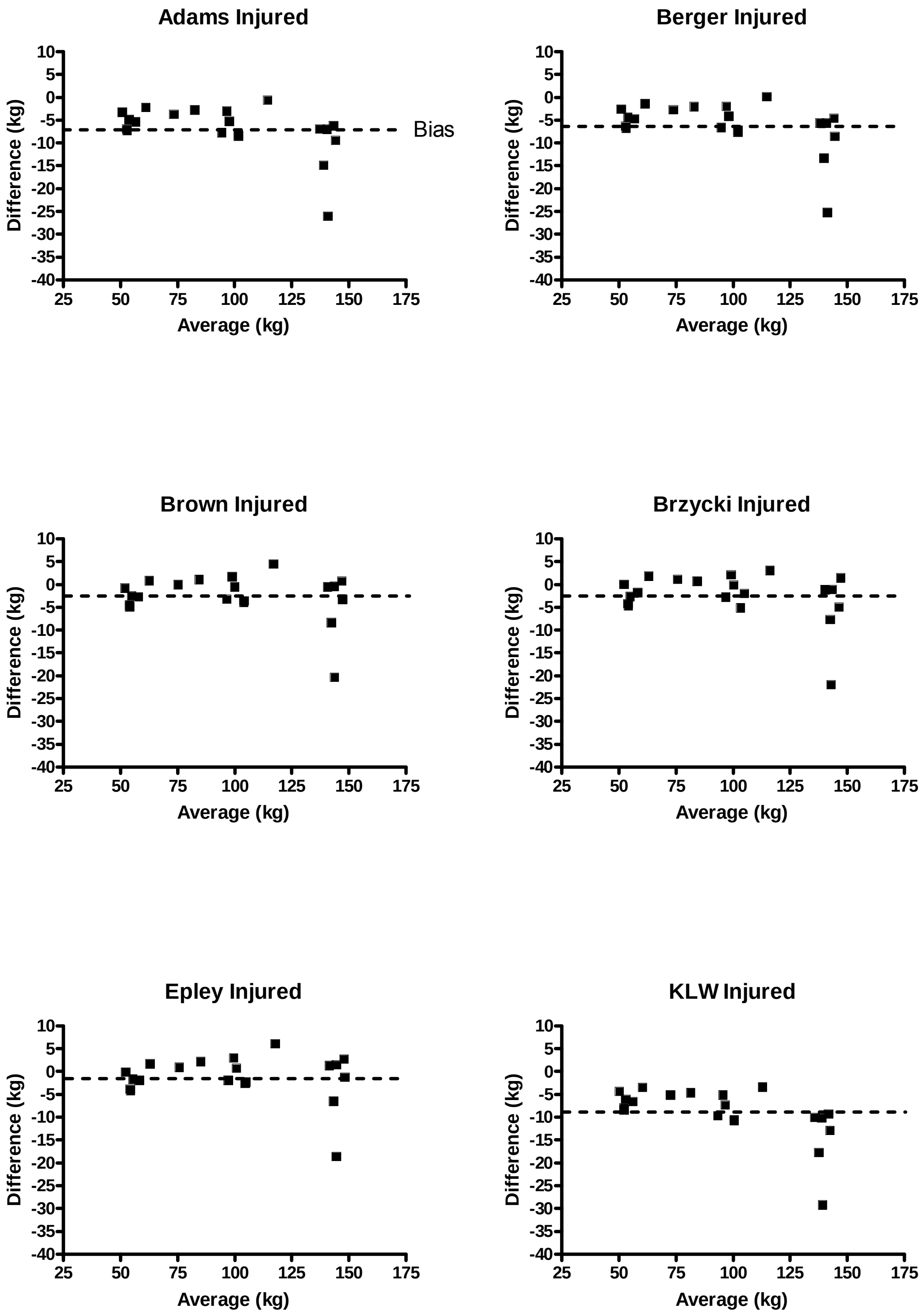

Figure 4.1: Bland and Altman Graphs for the Affected Limbs of Knee Injury Subjects Performing the Knee Extension Exercise

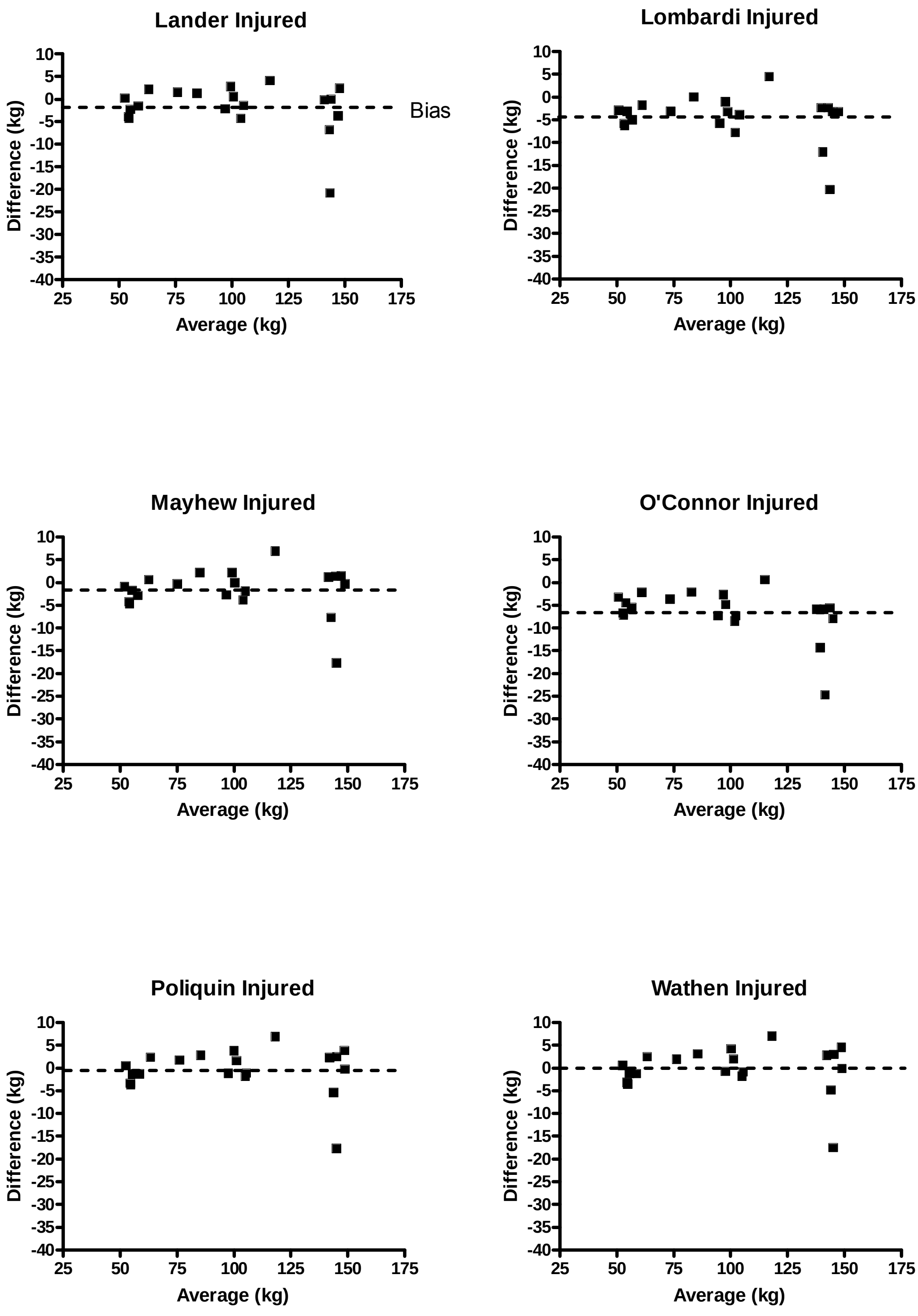

Figure 4.1 Continued: Bland and Altman Graphs for the Affected Limbs of Knee Injury Subjects Performing the Knee Extension Exercise

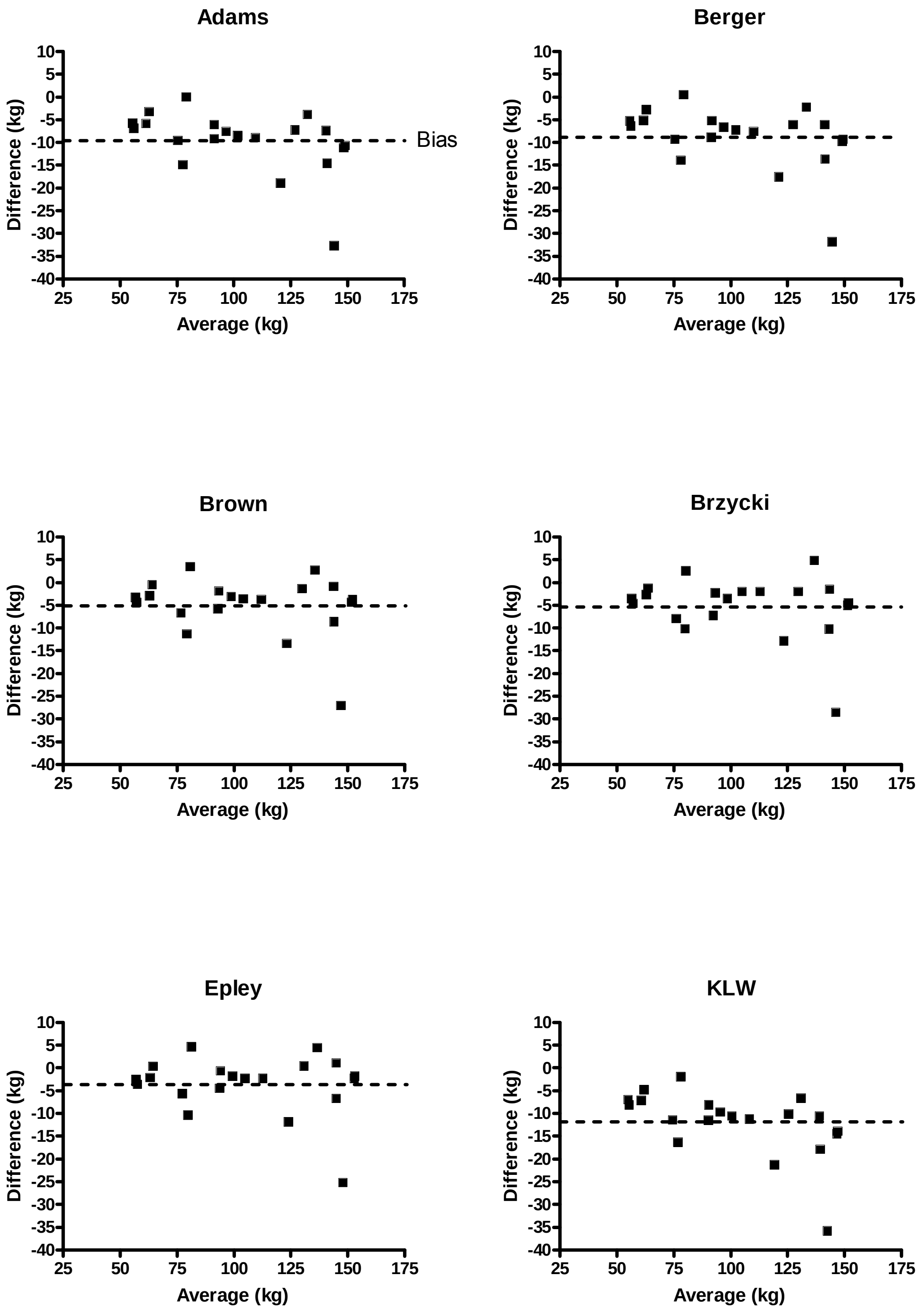

Figure 4.2: Bland and Altman Graphs for the Control Limbs of Knee Injury Subjects Performing the Knee Extension Exercise

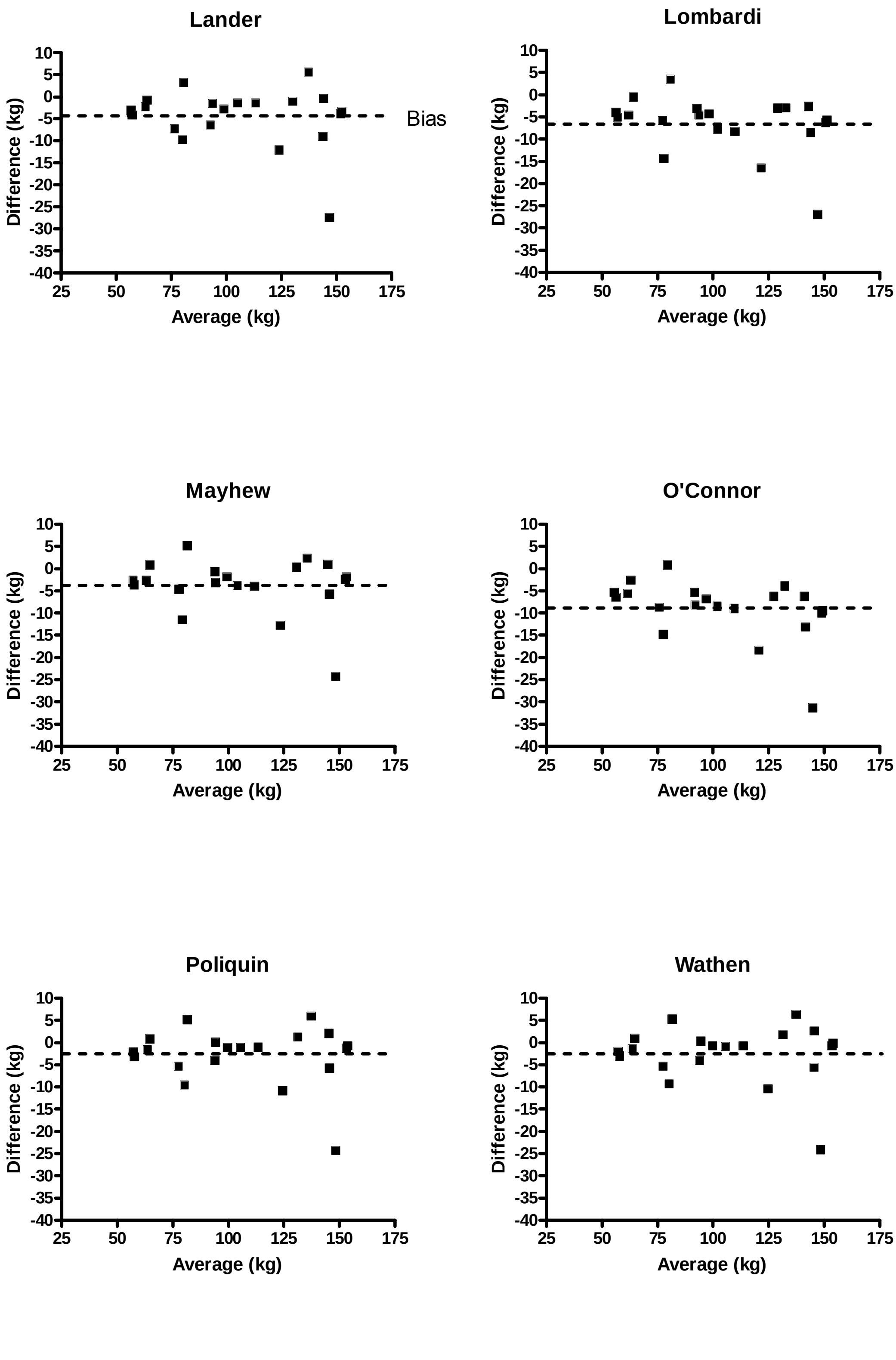

Figure 4.2 Continued: Bland and Altman Graphs for the Control Limbs of Knee Injury Subjects Performing the Knee Extension Exercise

Table 4.4: Statistical Analyses for the Affected Limbs of Knee Injury Subjects Performing the Knee Extension Exercise

Prediction Method	Bias (kg)	SD of Bias (kg)	95% Limits of Agreement	ICC	Lower Bound Confidence Interval	Typical Error (kg)	Typical Error as a Coefficient of Variation	95% Confidence Interval	Total Error	Subjects Within 5% of True 1-RM
Adams	-7.0	5.5	-17.8 to 3.7	.97	.56	3.9	3.1%	2.4 to 4.2%	6.2%	9/20 (45%)
Berger	-6.1	5.4	-16.7 to 4.5	.98	.72	3.8	3.1%	2.4 to 4.3%	5.5%	10/20 (50%)
Brown	-2.6	5.1	-12.5 to 7.4	.99	.97	3.6	3.1%	2.4 to 4.3%	3.6%	16/20 (80%)
Brzycki	-2.5	5.4	-13.1 to 8.1	.99	.96	3.8	3.2%	2.6 to 4.5%	3.6%	17/20 (85%)
Epley	-1.3	5.0	-11.1 to 8.6	.99	.98	3.6	3.1%	2.4 to 4.2%	3.2%	17/20 (85%)
KLW	-9.2	5.9	-20.7 to 2.4	.95	.25	4.2	3.1%	2.4 to 4.2%	7.7%	2/20 (10%)
Lander	-1.8	5.3	-12.2 to 8.6	.99	.97	3.8	3.2%	2.5 to 4.4%	3.4%	17/20 (85%)
Lombardi	-4.5	5.0	-14.2 to 5.3	.98	.89	3.5	3.2%	2.5 to 4.4%	4.7%	12/20 (60%)
Mayhew et al.	-1.7	4.9	-11.3 to 8.0	.99	.98	3.5	3.1%	2.4 to 4.2%	3.3%	16/20 (80%)
O'Connor	-6.5	5.3	-16.9 to 3.9	.97	.64	3.7	3.1%	2.4 to 4.2%	5.9%	10/20 (50%)
Poliquin	-0.5	5.0	-10.3 to 9.4	.99	.98	3.6	3.1%	2.4 to 4.3%	3.0%	16/20 (80%)
Wathen	-0.2	5.1	-10.1 to 9.7	.99	.98	3.6	3.1%	2.5 to 4.3%	3.0%	16/20 (80%)

SD = Standard deviation, ICC = Intraclass correlation coefficients

Table 4.5: Statistical Analyses for the Control Limbs of Knee Injury Subjects Performing the Knee Extension Exercise

Prediction Method	Bias (kg)	SD of Bias (kg)	95% Limits of Agreement	ICC	Lower Bound Confidence Interval	Typical Error (kg)	Typical Error as a Coefficient of Variation	95% Confidence Interval	Total Error	Subjects Within 5% of True 1-RM
Adams	-9.7	6.9	-23.2 to 3.9	.94	.27	4.9	3.8%	3.0 to 5.3%	7.9%	4/20 (20%)
Berger	-8.7	6.9	-22.2 to 4.7	.95	.41	4.9	3.8%	3.0 to 5.3%	7.3%	5/20 (25%)
Brown	-5.0	6.6	-17.9 to 7.9	.97	.87	4.6	3.8%	3.0 to 5.3%	5.1%	12/20 (60%)
Brzycki	-5.2	6.9	-18.8 to 8.3	.97	.86	4.9	3.9%	3.1 to 5.4%	5.3%	12/20 (60%)
Epley	-3.6	6.5	-16.4 to 9.1	.98	.93	4.6	3.8%	3.0 to 5.3%	4.5%	14/20 (70%)
KLW	-11.9	7.2	-26.1 to 2.3	.92	.08	5.1	3.8%	3.0 to 5.3%	9.5%	2/20 (10%)
Lander	-4.5	6.8	-17.9 to 8.9	.97	.90	4.8	3.9%	3.1 to 5.4%	4.9%	13/20 (65%)
Lombardi	-6.6	6.5	-19.3 to 6.1	.96	.71	4.6	4.0%	3.2 to 5.5%	6.0%	10/20 (50%)
Mayhew et al.	-3.8	6.4	-16.3 to 8.6	.98	.92	4.5	3.9%	3.1 to 5.4%	4.6%	14/20 (70%)
O'Connor	-9.0	6.8	-22.2 to 4.3	.95	.36	4.8	3.8%	3.0 to 5.3%	7.4%	5/20 (25%)
Poliquin	-2.9	6.5	-15.6 to 9.9	.98	.94	4.6	3.8%	3.0 to 5.3%	4.2%	15/20 (75%)
Wathen	-2.6	6.6	-15.5 to 10.3	.98	.95	4.6	3.9%	3.1 to 5.4%	4.2%	15/20 (75%)

SD = Standard deviation, ICC = Intraclass correlation coefficients

The Bland and Altman graphs show a random scatter of data for all of the prediction methods indicating that there were no systematic changes in error across the range of values. However, the results displayed in Figures 4.1 and 4.2 and in Tables 4.4 and 4.5 indicate that some prediction methods had a greater bias than others. In the affected limbs, the Adams, Berger, KLW, Lombardi and O'Connor equations exhibited greater bias (range: -9.2 to -4.5 kg) than the Brown, Brzycki, Epley, Lander, Mayhew et al., Poliquin and Wathen prediction methods (range -2.6 to -0.2 kg). In the control limbs, the former equations again exhibited greater bias (range: -11.9 to -6.6 kg) than the latter prediction methods (range -5.2 to -2.6 kg). The lowest levels of bias were produced by the Wathen equation in both the affected and control limbs (-0.2 kg and -2.6 kg, respectively).

With respect to the Bland and Altman 95% limits of agreement analysis, the Mayhew et al. equation exhibited the smallest interval for both the affected limbs (-11.3 to 8.0 kg) and control limbs (-16.3 to 8.6 kg). However, all of the other prediction methods, excluding the KLW equation, also produced similar values in both limbs.

Intraclass correlation coefficients were found to be high across all of the equations (range: 0.95 to 0.99 for the affected limbs and 0.92 to 0.98 for the control limbs). However, large differences were observed in the lower bound confidence intervals. In the affected limbs, the Adams, Berger, KLW, Lombardi and O'Connor equations produced the lowest values (range: 0.25 to 0.89), while the Brown, Brzycki, Epley, Lander, Mayhew et al., Poliquin and Wathen prediction methods produced the highest values (range: 0.96 to 0.98). In the control limbs, the former equations again produced the lowest values (range: 0.08 to 0.71), while the latter prediction methods produced the highest values (0.86 to 0.95).

Typical errors were small across all of the prediction methods, although they were larger in the control limbs than in the affected limbs. In both the affected limbs and the control limbs, the greatest typical errors were observed for the KLW equation (4.2 kg and 5.1 kg, respectively), while the smallest typical errors were observed for the Mayhew et al. equation (3.5 kg and 4.5 kg, respectively).

Typical errors as COVs were small across all of the prediction methods, although they were larger in the control limbs than in the affected limbs. In the affected limbs, the highest values were observed for the Brzycki, Lander, and Lombardi equations (3.2%), while the lowest values were observed for the Adams, Berger Brown, Epley, KLW, Mayhew et al., O'Connor, Poliquin and Wathen prediction methods (3.1%). In the control limbs, the highest values were observed for the Lombardi equation (4.0%), while the lowest values were observed for the Adams, Berger, Brown, Epley, KLW, O'Connor and Poliquin prediction methods (3.8%).

The total errors of measurement were greater in the control limbs than in the affected limbs. In the affected limbs, total errors were larger for the Adams, Berger, KLW, Lombardi and O'Connor equations (range: 4.7-7.7%) than for the Brown, Brzycki, Epley, Lander, Mayhew et al., Poliquin and Wathen prediction methods (range: 3.0-3.6%). In the control limbs, the former equations again produced the largest total errors (range: 6.0-9.5%), while the latter prediction methods produced the smallest total errors (range: 4.2-5.3%).

The number of subjects with predicted 1-RM values within 5% of their true 1-RM values differed greatly across the prediction equations. In the affected limbs, the Brown, Brzycki, Epley, Lander, Mayhew et al., Poliquin and Wathen prediction methods produced the greatest number of subjects with predicted 1-RM values within 5% of their true 1-RM (range: 80-85%), while the Adams, Berger, KLW, Lombardi and O'Connor equations produced the fewest (range: 10-60%). In the control limbs, the former prediction methods again produced the greatest number of subjects within 5% of their true 1-RM (range: 60-75%), while the latter equations produced the fewest (range: 10-50%).

Finally, the Bland and Altman graphs demonstrated that all of the prediction equations substantially underestimated knee extension 1-RM performance in one subject for both the affected limb (mean: -21.0 kg or -13.6%) and the control limb (mean: -27.6 kg or -17.2%). For this subject's affected limb, the percentage differences between predicted and actual 1-RM values for the Brzycki and Lander prediction equations were identified as significant outliers using a Grubbs' test (alpha level set at 0.05). In contrast, for this subjects control limb, none of the percentage differences for any of the prediction methods were identified as significant outliers. In addition, a second subject was identified as having much larger differences in predictive accuracy across the control and affected limbs than any of the other participants (mean percentage difference in control limb -13.9%; mean percentage difference in affected limb 0.6%). When the data from these subjects were excluded from the statistical analyses a number of changes were noted.

The results of the paired t-tests using the percentage difference scores demonstrated that there were no significant differences in predictive accuracy across the control and affected limbs for any of the prediction methods.

In the affected limbs, the bias for the more accurate prediction methods changed as follows: Epley (-0.5 kg), Lander (-1.0 kg), Mayhew et al. (-0.9 kg), Poliquin (0.3 kg) and Wathen (0.6 kg). In the control limbs, the bias for the more accurate prediction methods changed as follows: Epley (-2.1 kg), Lander (-2.9 kg), Mayhew et al. (-2.3 kg), Poliquin (-1.3 kg) and Wathen (-1.0 kg). Therefore, the lowest level of bias was now produced by the Poliquin equation for the affected limbs, although the Wathen equation continued to produce the lowest level of bias for the control limbs.

In the affected limbs, the 95% limits of agreement for the more accurate prediction methods changed as follows: Epley (-6.4 to 5.5 kg), Lander (-6.7 to 4.7 kg), Mayhew et al. (-7.4 to 5.6 kg), Poliquin (-5.8 to 6.4 kg) and Wathen (-5.5 to 6.8 kg). In the control limbs, the 95% limits of agreement for the more accurate prediction methods changed as follows: Epley (-9.6 to 5.4 kg), Lander (-10.9 to 5.2 kg), Mayhew et al. (-9.7 to 5.1 kg), Poliquin (-9.0 to 6.3 kg) and Wathen (-8.7 to 6.7 kg). Therefore, the Lander equation exhibited the smallest interval for the affected limbs and the Mayhew et al. equation exhibited the smallest interval for the control limbs. However, the intervals were similar for all of these equations.

In the affected limbs, the typical errors as COVs for the more accurate prediction methods changed as follows: Epley (2.5%), Lander (2.4%), Mayhew et al. (2.6%), Poliquin (2.4%) and Wathen (2.4%). In the control limbs, the typical errors as COVs also changed as follows: Epley (2.7%), Lander (2.8%), Mayhew et al. (2.7%), Poliquin (2.7%) and Wathen (2.7%). Therefore, the Lander, Poliquin and Wathen prediction methods now exhibited the smallest values for the affected limbs, while the Epley, Mayhew et al., Poliquin and Wathen prediction methods exhibited the smallest values for the control limbs.

In the affected limbs, the total errors of measurement for the more accurate prediction methods changed as follows: Epley (2.5%), Lander (2.5%), Mayhew et al. (2.8%), Poliquin (2.4%) and Wathen (2.4%). In the control limbs, the total errors of measurement also changed as follows: Epley (3.0%), Lander (3.5%), Mayhew et al. (3.1%), Poliquin (2.8%) and Wathen (2.8%). Therefore, the Poliquin and Wathen prediction methods now exhibited the smallest values for both limbs.

In summary, the Brown, Brzycki, Epley, Lander, Mayhew et al., Poliquin and Wathen prediction methods exhibited relatively low levels of bias and error for both the affected and control limbs during the knee extension exercise. In addition, these equations produced the greatest numbers of subjects within 5% or less of their actual 1-RM performance (ranges: affected limbs 80-85%; control limbs 60-75%). In contrast, the Adams, Berger, KLW, Lombardi and O'Connor equations exhibited higher levels of bias and error for both the affected and control limbs. In addition, these equations produced the fewest subjects within 5% or less of their actual 1-RM performance (ranges: affected limbs 10-60%; control limbs 10-50%).

4.3.1.2. Leg Press for Knee Injured Subjects

The mean group values for predicted and actual leg press 1-RM performance are displayed in Table 4.6. The mean values for actual leg press 1-RM performance were 83.7 kg (SD 28.4) for the affected limbs and 86.3 kg (SD 27.5) for the control limbs. These values were not significantly different ($p = 0.179$). The predicted leg press 1-RM values for the affected limbs ranged from 80.6 kg (28.6 SD) for the KLW equation to 88.3 kg (31.6 SD) for the Wathen equation. The predicted 1-RM values for the control limbs ranged from 83.6 kg (27.0 SD) for the KLW equation to 91.7 kg (29.8 SD) for the Wathen equation. The results of the paired t-tests demonstrated that there were no significant differences in predictive accuracy across the control and affected limbs for each of the prediction methods ($p > 0.05$).

Bland and Altman graphs were plotted to give an appreciation of the bias for the 1-RM prediction methods (see Figures 4.3 and 4.4). The bias, limits of agreement, ICCs, typical errors, typical errors as COVs, total errors of measurement and numbers of subjects within 5% or less of their true 1-RM are shown in Tables 4.7 and 4.8.

Table 4.6: Leg Press Actual and Predicted 1-RM Results

1-RM Method	Affected Limb Maximal Strength in kg (mean ± SD)	Control Limb Maximal Strength in kg (mean ± SD)
Actual 1-RM	83.7 ± 28.4	86.3 ± 27.5
Adams	82.6 ± 29.2	85.5 ± 27.6
Berger	83.3 ± 29.6	86.4 ± 28.0
Brown	86.3 ± 30.7	89.6 ± 29.0
Brzycki	86.1 ± 30.9	89.6 ± 29.2
Epley	87.5 ± 31.1	90.8 ± 29.4
KLW	80.6 ± 28.6	83.6 ± 27.0
Lander	86.8 ± 31.0	90.2 ± 29.4
Lombardi	85.2 ± 29.9	88.0 ± 28.3
Mayhew et al.	87.5 ± 30.9	90.5 ± 29.1
O'Connor	83.1 ± 29.4	86.1 ± 27.8
Poliquin	88.1 ± 31.4	91.5 ± 29.7
Wathen	88.3 ± 31.6	91.7 ± 29.8

The Bland and Altman graphs show a random scatter of data for all of the prediction methods indicating that there were no systematic changes in error across the range of values. However, the results displayed in Figures 4.3 and 4.4 and in Tables 4.7 and 4.8 indicate that some prediction methods had a greater bias than others. In the affected limbs, the Brown, Brzycki, Epley, KLW, Lander, Mayhew et al., Poliquin and Wathen prediction methods exhibited greater bias (range: -3.1 to 4.6 kg) than the Adams, Berger, Lombardi and O'Connor equations (range: -1.1 to 1.5 kg). In the control limbs, the former prediction methods again exhibited greater levels of bias (range: -2.7 to 5.4 kg) than the latter equations (range: -0.8 to 1.7 kg). The lowest levels of bias were produced by the Berger equation in both the affected and control limbs (-0.4 kg and 0.1 kg, respectively).

With respect to the 95% limits of agreement from the Bland and Altman analysis, the KLW equation exhibited the smallest intervals for the affected limbs (-9.2 to 3.0 kg) and the control limbs (-9.3 to 3.8 kg). However, the Adams, Berger, Lombardi and

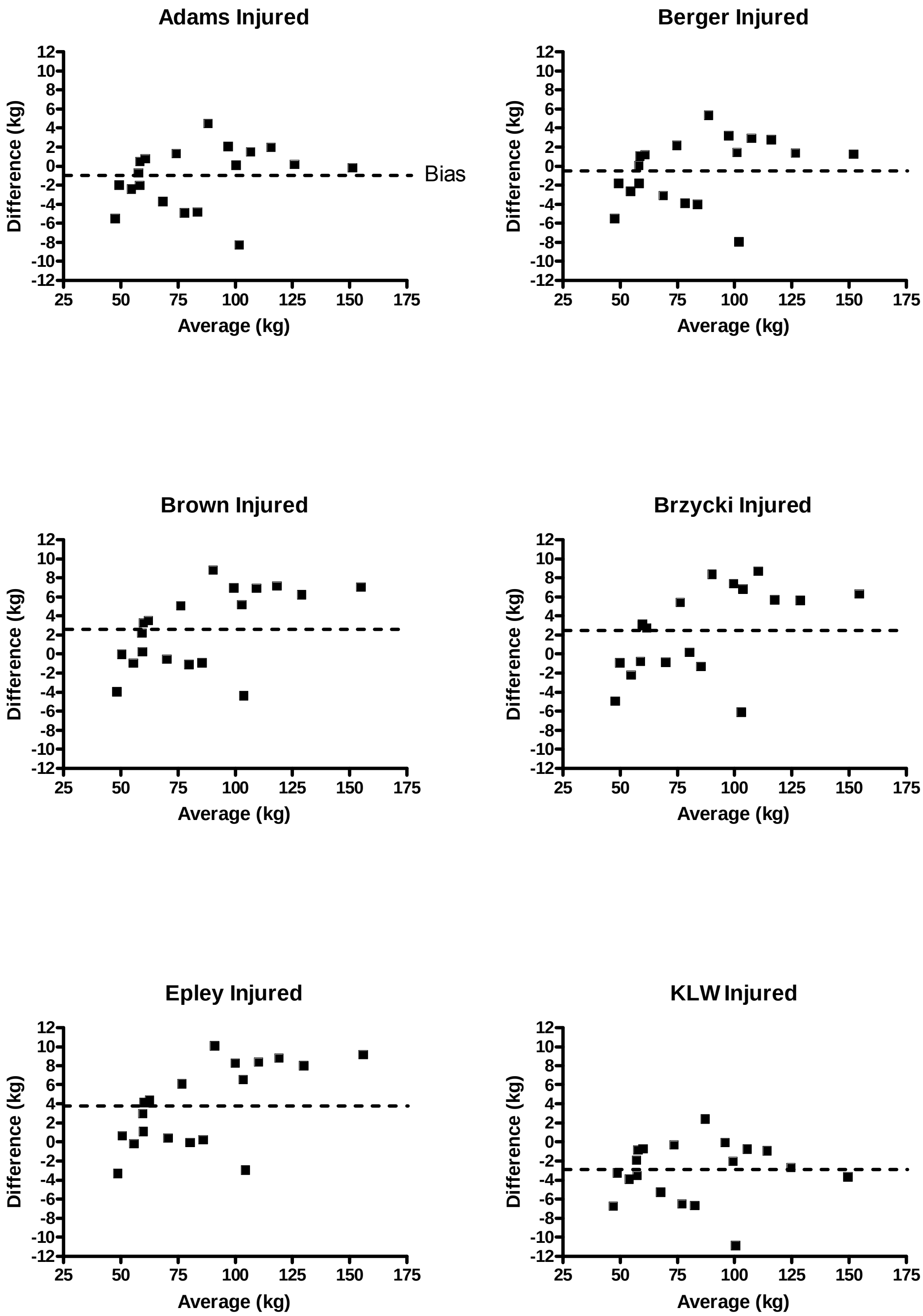

Figure 4.3: Bland and Altman Graphs for the Affected Limbs of Knee Injury Subjects Performing the Leg Press Exercise

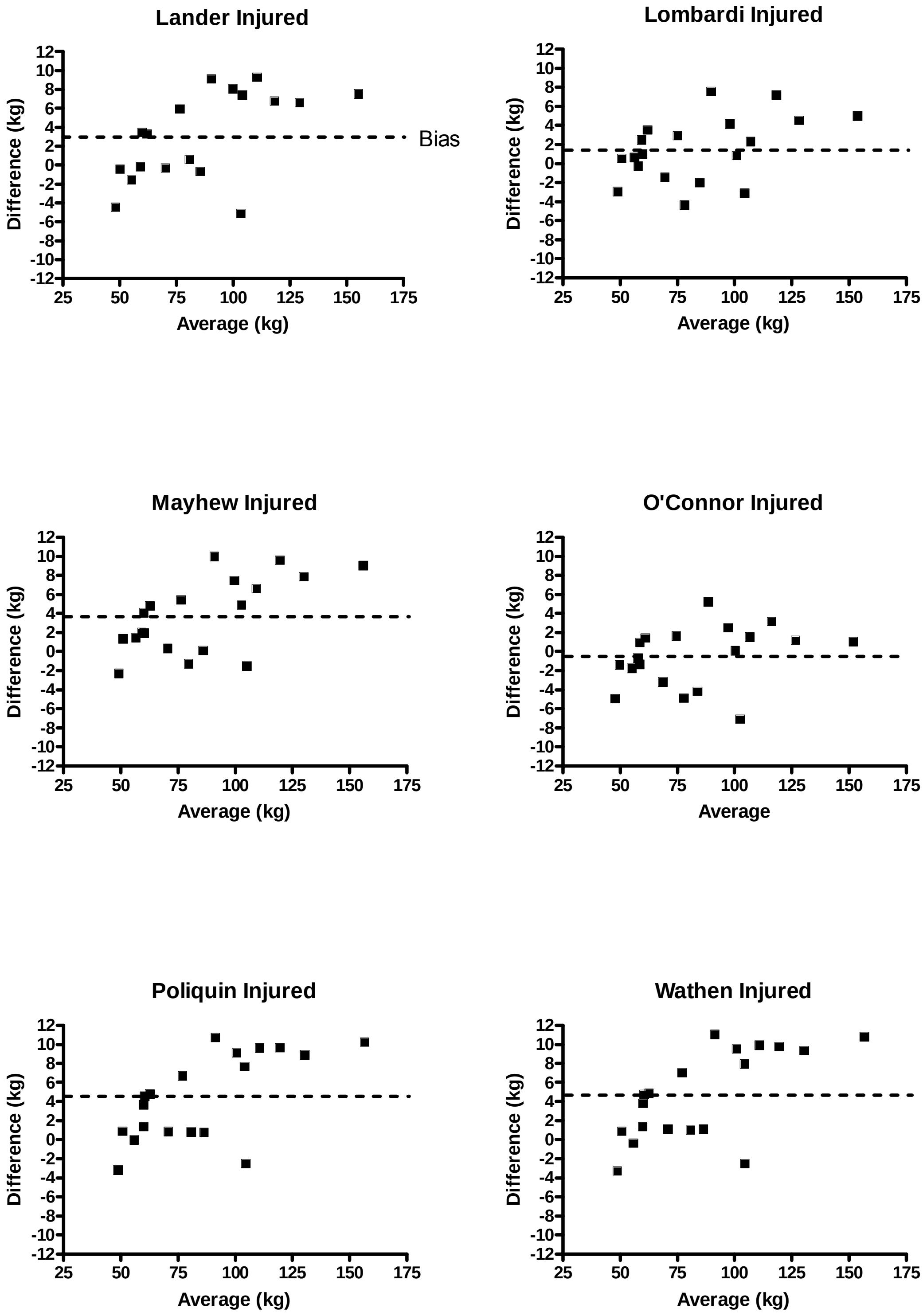

Figure 4.3 Continued: Bland and Altman Graphs for the Affected Limbs of Knee Injury Subjects Performing the Leg Press Exercise

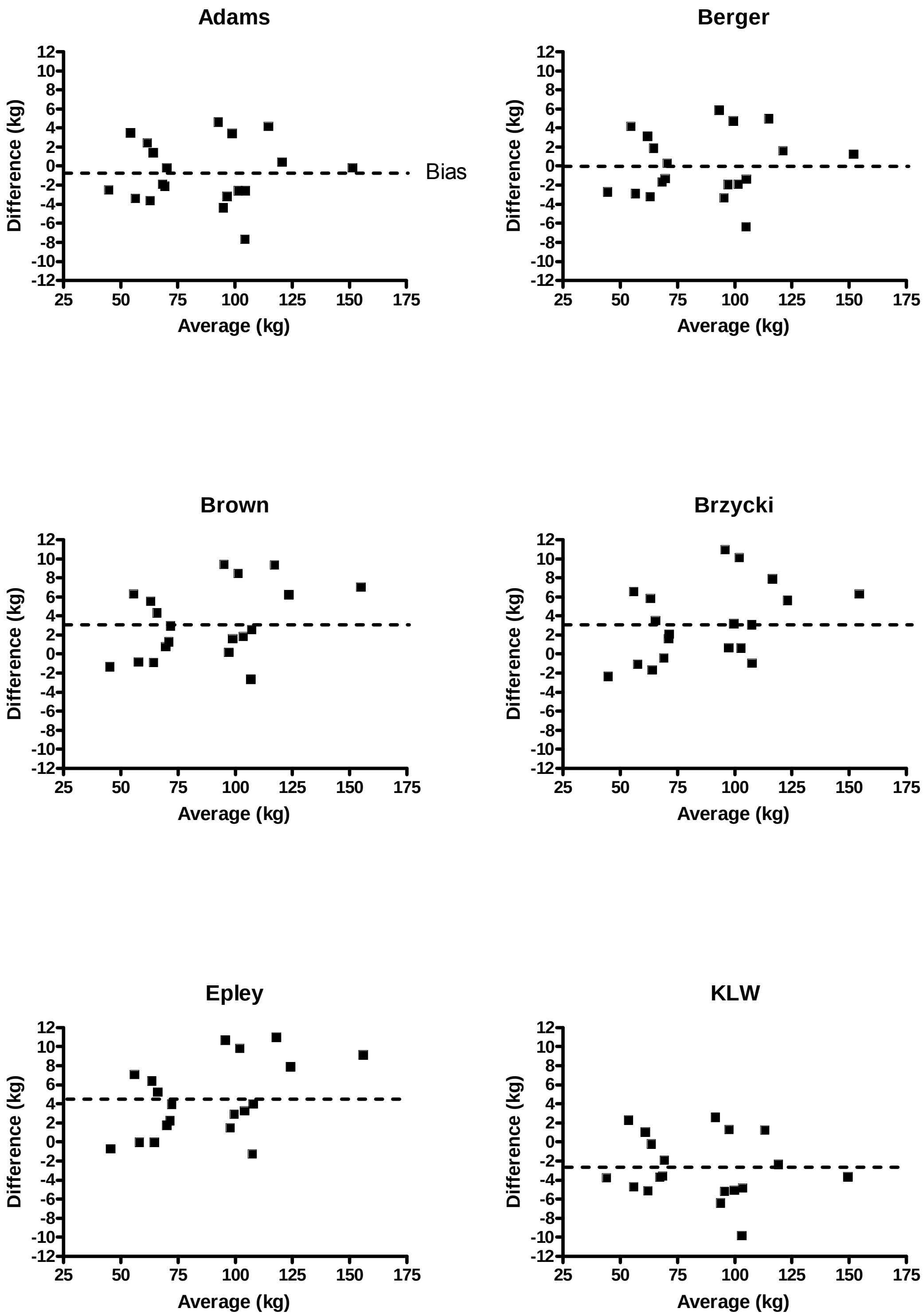

Figure 4.4: Bland and Altman Graphs for the Control Limbs of Knee Injury Subjects Performing the Leg Press Exercise

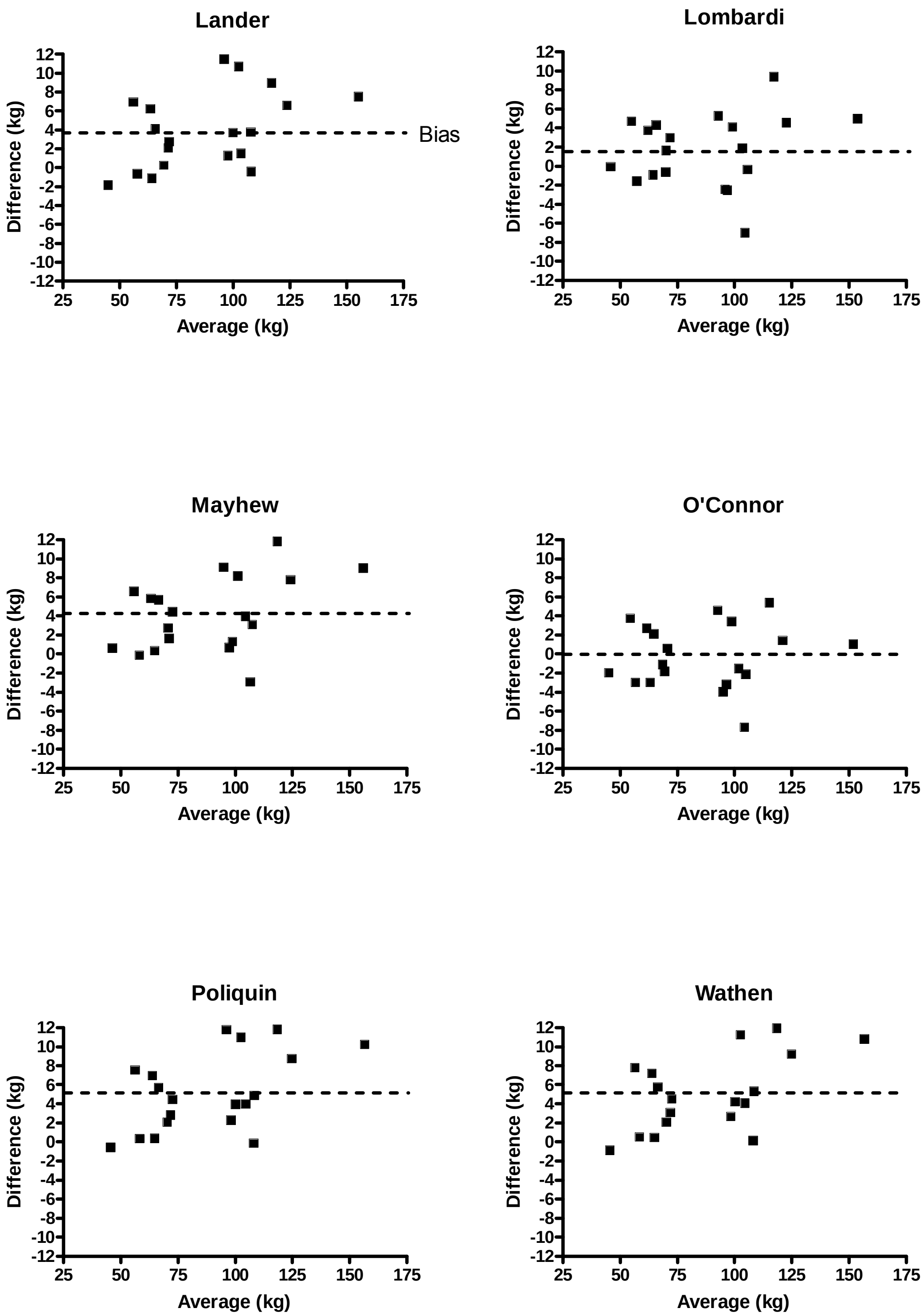

Figure 4.4 Continued: Bland and Altman Graphs for the Control Limbs of Knee Injury Subjects Performing the Leg Press Exercise

Table 4.7: Statistical Analyses for the Affected Limbs of Knee Injury Subjects Performing the Leg Press Exercise

Prediction Method	Bias (kg)	SD of Bias (kg)	95% Limits of Agreement	ICC	Lower Bound Confidence Interval	Typical Error (kg)	Typical Error as a Coefficient of Variation	95% Confidence Interval	Total Error	Subjects Within 5% of True 1-RM
Adams	-1.1	3.2	-7.4 to 5.1	.99	.98	2.3	3.0%	2.4 to 4.2%	3.3%	15/19 (79%)
Berger	-0.4	3.4	-7.2 to 6.3	.99	.98	2.4	3.2%	2.5 to 4.5%	3.2%	16/19 (84%)
Brown	2.7	4.1	-5.3 to 10.6	.99	.95	2.9	3.3%	2.6 to 4.6%	3.7%	11/19 (58%)
Brzycki	2.4	4.5	-6.4 to 11.3	.99	.96	3.2	3.8%	3.0 to 5.4%	4.0%	12/19 (63%)
Epley	3.8	4.3	-4.6 to 12.3	.98	.88	3.1	3.3%	2.6 to 4.6%	4.2%	8/19 (42%)
KLW	-3.1	3.1	-9.2 to 3.0	.99	.90	2.2	3.1%	2.5 to 4.4%	4.4%	11/19 (58%)
Lander	3.1	4.6	-5.9 to 12.0	.98	93	3.2	3.7%	2.9 to 5.2%	4.2%	10/19 (53%)
Lombardi	1.5	3.4	-5.2 to 8.1	.99	.98	2.4	2.8%	2.2 to 3.9%	2.9%	15/19 (79%)
Mayhew et al.	3.8	3.9	-3.9 to 11.5	.98	.87	2.8	2.9%	2.3 to 4.0%	4.0%	10/19 (53%)
O'Connor	-0.6	3.2	-6.8 to 5.7	.99	.99	2.2	2.9%	2.3 to 4.1%	3.0%	15/19 (79%)
Poliquin	4.4	4.6	-4.5 to 13.3	.98	.82	3.2	3.4%	2.7 to 4.7%	4.7%	7/19 (37%)
Wathen	4.6	4.7	-4.6 to 13.8	.98	.81	3.3	3.5%	2.8 to 4.9%	4.8%	7/19 (37%)

SD = Standard deviation, ICC = Intraclass correlation coefficients

Table 4.8: Statistical Analyses for the Control Limbs of Knee Injury Subjects Performing the Leg Press Exercise

Prediction Method	Bias (kg)	SD of Bias (kg)	95% Limits of Agreement	ICC	Lower Bound Confidence Interval	Typical Error (kg)	Typical Error as a Coefficient of Variation	95% Confidence Interval	Total Error	Subjects Within 5% of True 1-RM
Adams	-0.8	3.3	-7.3 to 5.8	.99	.98	2.4	3.0%	2.3 to 4.2%	3.0%	15/19 (79%)
Berger	0.1	3.4	-6.6 to 6.7	.99	.98	2.4	3.1%	2.4 to 4.3%	3.0%	15/19 (79%)
Brown	3.3	3.8	-4.1 to 10.6	.99	.90	2.7	3.1%	2.5 to 4.3%	4.0%	13/19 (68%)
Brzycki	3.2	4.0	-4.6 to 11.0	.98	.91	2.8	3.5%	2.7 to 4.8%	4.2%	13/19 (68%)
Epley	4.5	4.0	-3.3 to 12.2	.98	.75	2.8	3.1%	2.4 to 4.3%	4.7%	10/19 (53%)
KLW	-2.7	3.3	-9.3 to 3.8	.99	.93	2.4	3.0%	2.4 to 4.2%	3.8%	14/19 (74%)
Lander	3.9	4.0	-4.0 to 11.8	.98	.85	2.9	3.4%	2.7 to 4.7%	4.5%	13/19 (68%)
Lombardi	1.7	3.8	-5.7 to 9.1	.99	.97	2.7	3.0%	2.4 to 4.2%	3.2%	13/19 (68%)
Mayhew et al.	4.2	3.9	-3.4 to 11.8	.98	.79	2.8	2.9%	2.3 to 4.1%	4.4%	10/19 (53%)
O'Connor	-0.2	3.4	-6.9 to 6.4	.99	.98	2.4	2.9%	2.3 to 4.1%	2.9%	17/19 (89%)
Poliquin	5.2	4.1	-2.9 to 13.2	.97	.63	2.9	3.2%	2.5 to 4.4%	5.1%	10/19 (53%)
Wathen	5.4	4.2	-2.9 to 13.6	.97	.59	3.0	3.2%	2.5 to 4.5%	5.3%	10/19 (53%)

SD = Standard deviation, ICC = Intraclass correlation coefficients

O'Connor equations also produced similar values in the affected limbs, while the Adams, Berger, and O'Connor equations produced similar values in the control limbs.

Intraclass correlation coefficients were found to be high across all of the equations (range: 0.98 to 0.99 for the affected limbs and 0.97 to 0.99 for the control limbs). However, differences were observed in the lower bound confidence intervals. In the affected limbs, the Epley, KLW, Mayhew et al., Poliquin and Wathen prediction methods produced the lowest values (range: 0.81 to 0.90), while the Adams, Berger, Brown, Brzycki, Lander, Lombardi and O'Connor equations produced the highest values (range: 0.95 to 0.99). In the control limbs, the Epley, Mayhew et al., Poliquin and Wathen prediction methods produced the lowest values (range: 0.59 to 0.79), while the Adams, Berger, Brown, Brzycki, KLW, Lander, Lombardi and O'Connor equations produced the highest values (range: 0.90 to 0.98).

Typical errors were small across all of the prediction equations. In the affected limbs, the greatest typical error was observed for the Wathen equation (3.3 kg) while the smallest typical error was observed for the KLW equation (2.2 kg). In the control limbs, the greatest typical error was observed for the Wathen equation (3.0 kg) while the smallest typical error was observed for the Adams and KLW equations (2.4 kg).

Typical errors as COVs were small across all of the prediction methods. In the affected limbs, the highest value was observed for the Brzycki equation (3.8%), while the lowest value was observed for the Lombardi equation (2.8%). In the control limbs, the highest value was observed for the Brzycki equation (3.5%), while the lowest value was observed for the Mayhew et al. and O'Connor equations (2.9%).

The total errors of measurement were similar across the affected and control limbs. In the affected limbs, total errors were larger for the Brown, Brzycki, Epley, KLW, Lander, Mayhew et al., Poliquin and Wathen prediction methods (range: 3.7-4.8%) than for the Adams, Berger, Lombardi and O'Connor equations (range: 2.9-3.3%). In the control limbs, the former prediction methods again produced larger total error values (range: 3.8-5.3%) than the latter equations (range: 2.9-3.2%).

The number of subjects with predicted 1-RM values within 5% of their true 1-RM values differed greatly across the prediction equations. In the affected limbs, the

Adams, Berger, Lombardi and O'Connor equations produced the greatest number of subjects with predicted 1-RM values within 5% of their true 1-RM (range: 79-84%), while the Brown, Brzycki, Epley, KLW, Lander, Mayhew et al., Poliquin and Wathen prediction methods produced the fewest (range: 37-63%). In the control limbs, the Adams, Berger, and O'Connor equations produced the greatest number of subjects with predicted 1-RM values within 5% of their true 1-RM (79-89%), while the Brown, Brzycki, Epley, KLW, Lander, Lombardi Mayhew et al., Poliquin and Wathen prediction methods produced the fewest (53-74%).

In summary, the Adams, Berger Lombardi and O'Connor equations exhibited relatively low levels of bias and error for both the affected (ranges: bias -1.1 to 1.5 kg; typical error as a COV 2.8-3.2%; total error 2.9-3.3%) and control (ranges: bias -0.8 to 1.7 kg; typical error as a COV 2.9-3.1%; total error 2.9-3.2%) limbs when the knee injury group performed the leg press exercise. In addition, these equations produced the greatest numbers of subjects within 5% or less of their actual 1-RM performance (ranges: affected limbs 79-84%; control limbs 79-89%). In contrast, the Brown, Brzycki, Epley, KLW, Lander, Mayhew et al., Poliquin and Wathen prediction methods exhibited higher levels of bias and error for both the affected (ranges: bias -3.1 to 4.6 kg; typical error as a COV 2.9-3.8%; total error 3.7-4.8%) and control (ranges: bias -2.7 to 5.4 kg; typical error as a COV 2.9-3.5%; total error 3.8-5.3%) limbs. In addition, these equations produced the fewest subjects within 5% or less of their true 1-RM performance (ranges: affected limbs 37-63%; control limbs 53-74%).

4.3.2. Knee OA Subjects

4.3.2.1. Knee Extension for Knee OA Subjects

The mean group values for predicted and actual 1-RM performance for the affected and control limbs are displayed in Table 4.9. The mean values for actual knee extension 1-RM performance were 66.5 kg (SD 27.6) for the affected limbs and 82.3 (SD 33.6) for the control limbs. These values were significantly different ($p < 0.05$). The predicted knee extension 1-RM values for the affected limbs ranged from 60.5 kg (25.2 SD) for the KLW equation to 66.5 kg (27.7 SD) for the Wathen equation. The predicted 1-RM values for the control limbs ranged from 73.8 kg (29.0 SD) for the

KLW equation to 81.1 kg (31.8 SD) for the Wathen equation. The paired t-tests using the percentage difference scores ((predicted 1- RM – actual 1-RM) / actual 1-RM) demonstrated that there were no significant differences in predictive accuracy across the control and affected limbs for each of the prediction methods ($p > 0.05$).

Table 4.9: Knee Extension Actual and Predicted 1-RM Results

1-RM Method	Affected Limb Maximal Strength in kg (mean ± SD)	Control Limb Maximal Strength in kg (mean ± SD)
Actual 1-RM	66.5 ± 27.6	82.3 ± 33.6
Adams	61.8 ± 25.7	75.5 ± 29.7
Berger	62.5 ± 26.1	76.3 ± 30.0
Brown	64.9 ± 27.0	79.2 ± 31.1
Brzycki	65.2 ± 27.3	79.5 ± 31.1
Epley	65.7 ± 27.4	80.2 ± 31.5
KLW	60.5± 25.2	73.8 ± 29.0
Lander	65.7 ± 27.5	80.0 ± 31.3
Lombardi	63.1 ± 26.1	77.2 ± 30.7
Mayhew et al.	65.2 ± 27.0	79.6 ± 31.5
O'Connor	62.1 ± 25.8	75.8 ± 30.0
Poliquin	66.3 ± 27.6	80.9 ± 31.8
Wathen	66.5 ± 27.7	81.1 ± 31.8

Bland and Altman graphs were plotted to give an appreciation of the bias for each of the prediction methods (see Figures 4.5 and 4.6). The bias, limits of agreement, ICCs, typical errors, typical errors as COVs, total errors of measurement and numbers of subjects within 5% of their true 1-RM are shown in Tables 4.10 and 4.11.

The Bland and Altman graphs show a random scatter of data for all of the prediction methods indicating that there were no systematic changes in error across the range of values. However, the results displayed in Figures 4.5 and 4.6 and in Tables 4.10 and

4.11 indicate that some prediction methods had a greater bias than others. In the affected limbs, the Adams, Berger, KLW, Lombardi and O'Connor equations exhibited greater bias (range: -6.0 to -3.4 kg) than the Brown, Brzycki, Epley, Lander, Mayhew et al., Poliquin and Wathen prediction methods (range -1.6 to 0.0 kg). In the control limbs, the former equations again exhibited greater bias (range: -8.5 to -5.1 kg) than the latter prediction methods (range -3.1 to -1.1 kg). The lowest levels of bias were produced by the Wathen equation in both the affected and control limbs (0.0 kg and -1.1 kg, respectively).

With respect to the 95% limits of agreement from the Bland and Altman analysis, the Mayhew et al. equation exhibited the smallest interval for both the affected limbs (-9.8 to 7.2 kg) and control limbs (-12.5 to 7.3 kg). However, in the affected limbs, all of the other equations also produced similar 95% limits of agreement intervals. In contrast, only the Brown, Epley, Lombardi, Poliquin and Wathen prediction methods produced similar intervals in the control limbs.

Intraclass correlation coefficients were found to be high across all of the equations (range: 0.96 to 0.99 for the affected limbs and 0.95 to 0.99 for the control limbs). However, large differences were observed in the lower bound confidence intervals. In the affected limbs, the Adams, Berger, KLW, Lombardi and O'Connor equations produced the lowest values (range: 0.49 to 0.89), while the Brown, Brzycki, Epley, Lander, Mayhew et al., Poliquin and Wathen prediction methods produced the highest values (range: 0.95 to 0.96). In the control limbs, the former equations again produced the lowest values (range: 0.35 to 0.79), while the latter prediction methods produced the highest values (range: 0.93 to 0.96).

Typical errors were small across all of the equations. In both the affected and control limbs, the largest typical errors were observed for the KLW equation (3.5 kg and 4.6 kg, respectively), while the smallest typical errors were observed for the Mayhew et al. equation (3.1 kg and 3.6 kg, respectively).

The typical errors as COVs were small across all of the prediction methods. In the affected limbs, the highest value was observed for the Brzycki and Lander equations (4.0%), while the lowest value was observed for the Adams, Berger, Brown, Epley, KLW, Lombardi, Mayhew et al. and O'Connor equations (3.8%). In the control limbs,

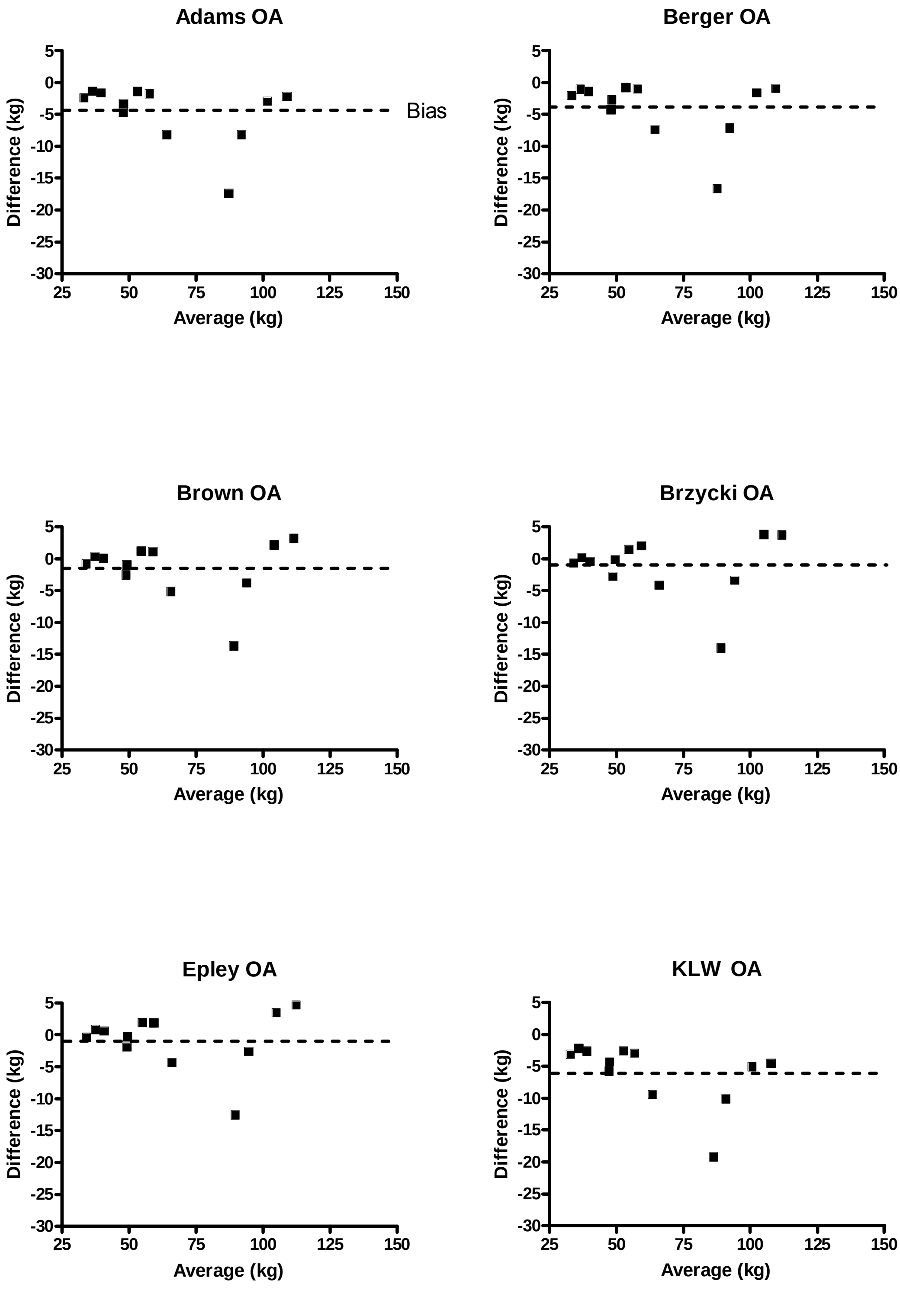

Figure 4.5: Bland and Altman Graphs for the Affected Limbs of Knee OA Subjects Performing the Knee Extension Exercise

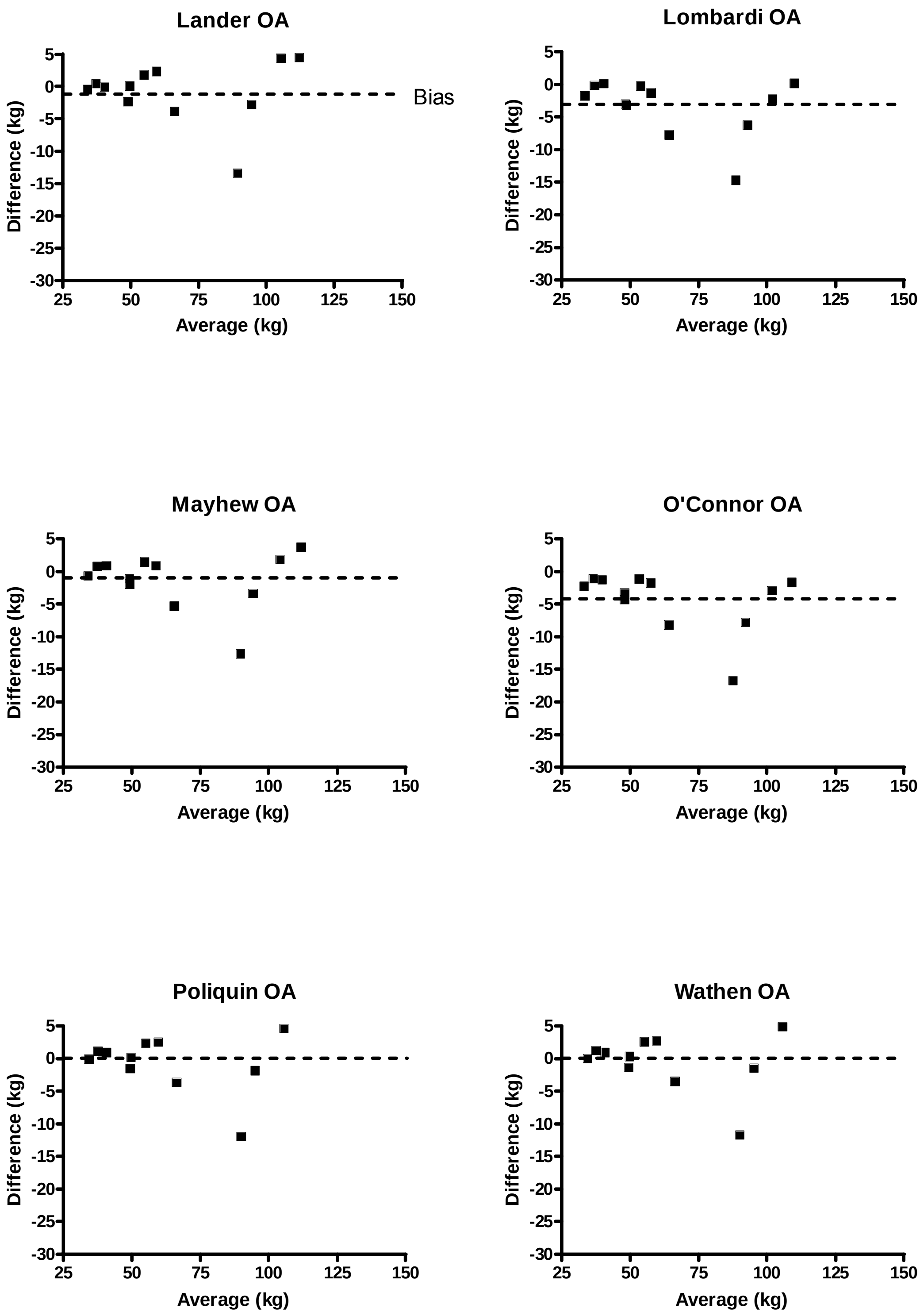

Figure 4.5 Continued: Bland and Altman Graphs for the Affected Limbs of Knee OA Subjects Performing the Knee Extension Exercise

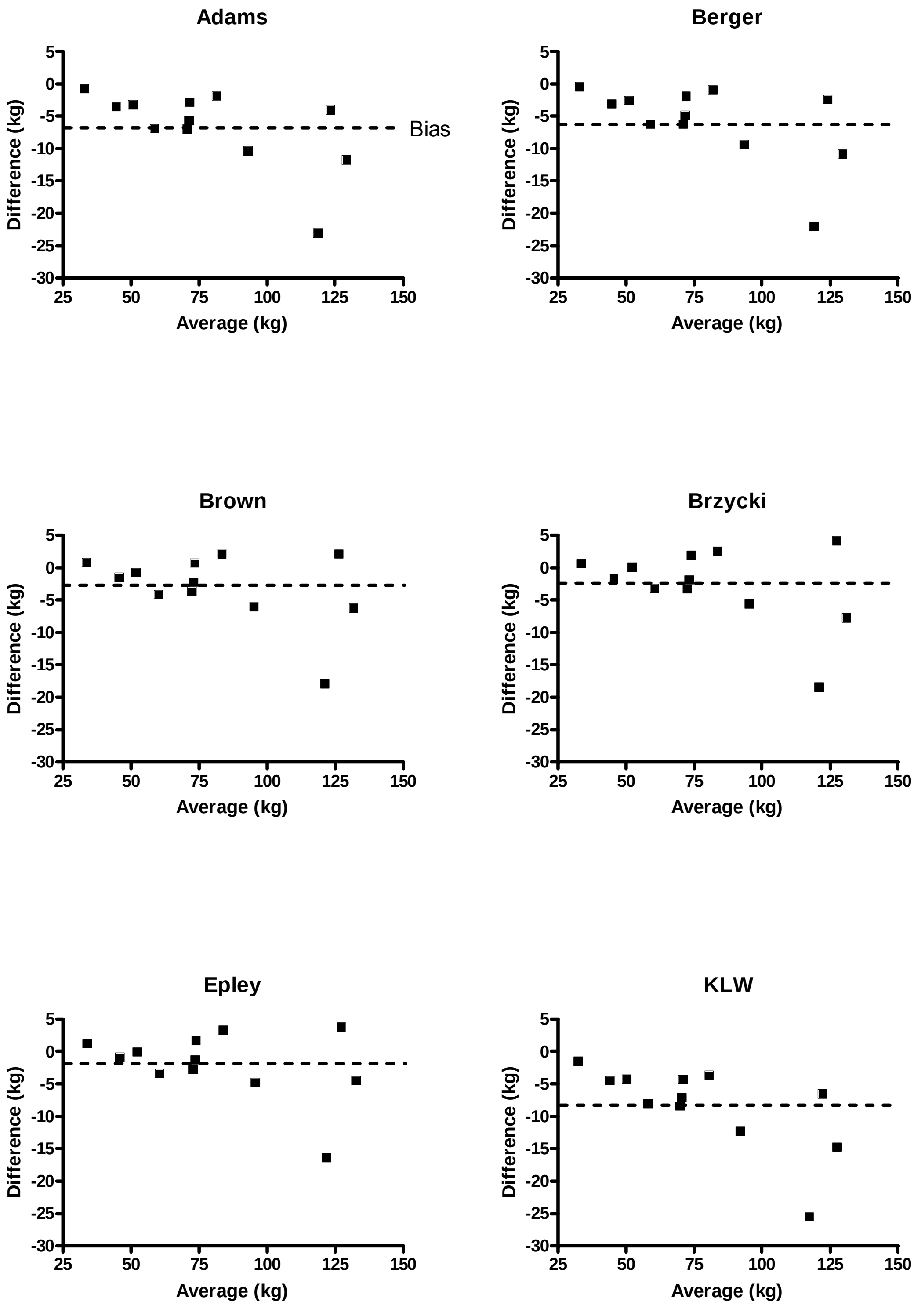

Figure 4.6: Bland and Altman Graphs for the Control Limbs of Knee OA Subjects Performing the Knee Extension Exercise

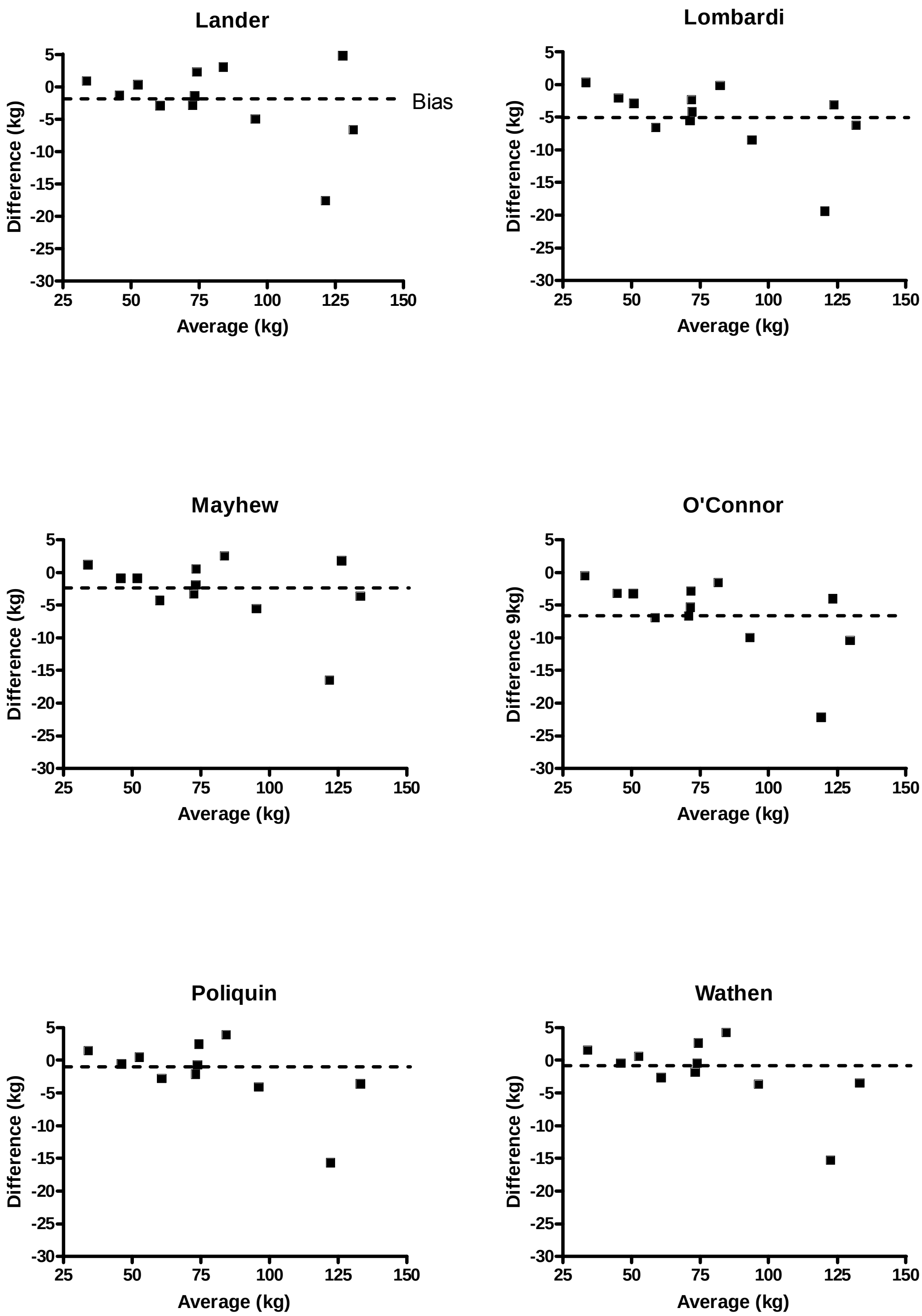

Figure 4.6 Continued: Bland and Altman Graphs for the Control Limbs of Knee OA Subjects Performing the Knee Extension Exercise

Table 4.10: Statistical Analyses for the Affected Limbs of Knee OA Subjects Performing the Knee Extension Exercise

Prediction Method	Bias (kg)	SD of Bias (kg)	95% Limits of Agreement	ICC	Lower Bound Confidence Interval	Typical Error (kg)	Typical Error as a Coefficient of Variation	95% Confidence Interval	Total Error	Subjects Within 5% of True 1-RM
Adams	-4.7	4.7	-13.8 to 4.6	.97	.74	3.3	3.8%	2.8 to 6.0%	6.3%	6/12 (50%)
Berger	-3.9	4.6	-13.0 to 5.2	.98	.84	3.3	3.8%	2.9 to 6.0%	5.7%	7/12 (50%)
Brown	-1.6	4.5	-10.4 to 7.2	.99	.95	3.2	3.8%	2.9 to 6.0%	4.0%	10/12 (83%)
Brzycki	-1.2	4.8	-10.6 to 8.1	.99	.95	3.4	4.0%	3.0 to 6.3%	4.1%	9/12 (75%)
Epley	-0.8	4.5	-9.6 to 8.1	.99	.96	3.2	3.8%	2.9 to 6.0%	3.7%	10/12 (83%)
KLW	-6.0	4.9	-15.6 to 3.6	.96	.49	3.5	3.8%	2.9 to 6.0%	7.8%	4/12 (33%)
Lander	-0.8	4.8	-10.1 to 8.5	.99	.95	3.4	4.0%	3.0 to 6.3%	3.9%	10/12 (83%)
Lombardi	-3.4	4.4	-11.9 to 5.2	.98	.89	3.1	3.8%	2.8 to 5.9%	5.1%	7/12 (58%)
Mayhew et al.	-1.3	4.3	-9.8 to 7.2	.99	.96	3.1	3.8%	2.8 to 5.9%	3.8%	10/12 (83%)
O'Connor	-4.4	4.6	-13.4 to 4.6	.97	.77	3.3	3.8%	2.8 to 5.9%	6.1%	6/12 (50%)
Poliquin	-0.2	4.6	-9.1 to 8.8	.99	.96	3.2	3.9%	2.9 to 6.1%	3.7%	11/12 (92%)
Wathen	0.0	4.6	-8.9 to 9.0	.99	.96	3.2	3.9%	2.9 to 6.0%	3.7%	11/12 (92%)

SD = Standard deviation, ICC = Intraclass correlation coefficients

Table 4.11: Statistical Analyses for the Control Limbs of Knee OA Subjects Performing the Knee Extension Exercise

Prediction Method	Bias (kg)	SD of Bias (kg)	95% Limits of Agreement	ICC	Lower Bound Confidence Interval	Typical Error (kg)	Typical Error as a Coefficient of Variation	95% Confidence Interval	Total Error	Subjects Within 5% of True 1-RM
Adams	-6.8	6.1	-18.7 to 5.2	.96	.59	4.3	3.5%	2.6 to 5.5%	6.8%	4/12 (33%)
Berger	-5.9	6.0	-17.7 to 5.9	.97	.72	4.3	3.6%	2.7 to 5.6%	6.1%	5/12 (42%)
Brown	-3.1	5.5	-13.9 to 7.7	.98	.93	3.9	3.6%	2.7 to 5.6%	4.1%	9/12 (75%)
Brzycki	-2.8	6.0	-14.5 to 9.0	.98	.93	4.3	3.8%	2.9 to 6.0%	4.2%	9/12 (75%)
Epley	-2.0	5.3	-12.5 to 8.4	.99	.95	3.8	3.6%	2.7 to 5.6%	3.7%	11/12 (92%)
KLW	-8.5	6.6	-21.3 to 4.4	.95	.35	4.6	3.6%	2.7 to 5.6%	8.3%	3/12 (25%)
Lander	-2.2	5.9	-13.7 to 9.3	.98	.94	4.2	3.8%	2.8 to 6.0%	3.9%	11/12 (92%)
Lombardi	-5.1	5.2	-15.3 to 5.2	.98	.79	3.7	3.4%	2.5 to 5.3%	5.4%	6/12 (50%)
Mayhew et al.	-2.6	5.1	-12.5 to 7.3	.99	.95	3.6	3.4%	2.6 to 5.4%	3.8%	9/12 (75%)
O'Connor	-6.4	5.9	-17.9 to 5.0	.97	.63	4.1	3.5%	2.6 to 5.4%	6.5%	4/12 (33%)
Poliquin	-1.4	5.4	-11.9 to 9.1	.99	.96	3.8	3.6%	2.7 to 5.6%	3.5%	11/12 (92%)
Wathen	-1.1	5.3	-11.6 to 9.3	.99	.96	3.8	3.6%	2.7 to 5.6%	3.5%	11/12 (92%)

SD = Standard deviation, ICC = Intraclass correlation coefficients

the highest value was observed for the Brzycki and Lander equations (3.8%), while the lowest value was observed for the Lombardi and Mayhew et al. equations (3.4%).

Total errors of measurement were similar across the affected and control limbs. In the affected limbs, total errors were greater for the Adams, Berger, KLW, Lombardi and O'Connor equations (range: 5.1-7.8%) than for the Brown, Brzycki, Epley, Lander, Mayhew et al., Poliquin and Wathen prediction methods (range: 3.7-4.1%). In the control limbs, total errors were again greater for the former equations (range: 5.4-8.3%) than for the latter prediction methods (range: 3.5-4.2%).

The number of subjects with predicted 1-RM values within 5% of their true 1-RM values differed greatly across the prediction equations. In the affected limbs, the Brown, Brzycki, Epley, Lander, Mayhew et al., Poliquin and Wathen prediction methods produced the greatest numbers of subjects within 5% of their true 1-RM (range: 75-92%), while the Adams, Berger, KLW, Lombardi and O'Connor equations produced the fewest (33-58%). In the control limbs, the former prediction methods again produced the greatest numbers of subjects within 5% of their true 1-RM (range: 75-92%), while the latter equations produced the fewest (25-50%).

Finally, the Bland and Altman graphs demonstrated that all of the prediction equations substantially underestimated knee extension 1-RM performance in one subject for both the affected limb (mean: -14.2 kg or -14.8%) and the control limb (mean: -18.6 kg or -14.3%). For this subject's affected limb, the percentage differences between predicted and actual 1-RM values for the Brzycki, Lander, Poliquin and Wathen prediction methods were identified as significant outliers using a Grubbs' test (alpha level set at 0.05). In contrast, for this subjects control limb, none of the percentage differences for any of the prediction methods were identified as significant outliers. When this subject's data were excluded from the statistical analyses, a number of changes were noted.

In the affected limbs, the bias for the more accurate prediction methods changed as follows: Brown (-0.5 kg), Brzycki (-0.1 kg), Epley (-0.3 kg), Lander (-0.3 kg), Mayhew et al. (-0.3 kg), Poliquin (0.9 kg) and Wathen (1.1 kg). In the control limbs the bias for the more accurate prediction methods changed as follows: Brown (-1.7 kg), Brzycki (-1.3 kg), Epley (-0.7 kg), Lander (-0.8 kg), Mayhew et al. (-1.4 kg), Poliquin (-0.1 kg) and Wathen (-1.1 kg). Therefore, the lowest level of bias was now produced by the Brzycki equation for the affected limbs, while the Poliquin table produced the lowest level of bias for the control limbs.

In the affected limbs, the 95% limits of agreement for the more accurate prediction methods changed as follows: Brown (-5.5 to 4.5 kg), Brzycki (-5.3 to 5.2 kg), Epley (-4.9 to 5.5 kg), Lander (-5.0 to 5.7 kg), Mayhew et al. (-5.3 to 4.8 kg), Poliquin (-4.5 to 6.3 kg) and Wathen (-4.4 to 6.6 kg). In the control limbs, the 95% limits of agreement for the more accurate prediction methods changed as follows: Brown (-7.7 to 4.2 kg), Brzycki (-8.3 to 5.7 kg), Epley (-6.5 to 5.1 kg), Lander (-7.6 to 6.0 kg), Mayhew et al. (-6.6 to 3.9 kg), Poliquin (-6.0 to 5.9 kg) and Wathen (-4.4 to 6.6 kg). Therefore, the Brown equation now exhibited the smallest interval for the affected limbs, while the Mayhew et al. equation exhibited the smallest interval for the control limbs.

In the affected limbs, the typical errors as COVs for the more accurate prediction methods changed as follows: Brown (2.5%), Brzycki (2.6 %), Epley (2.5%), Lander (2.6%), Mayhew et al. (2.6%), Poliquin (2.5%) and Wathen (2.5%). In the control limbs, the values for the more accurate prediction methods changed as follows: Brown (2.5%), Brzycki (2.7%), Epley (2.5%), Lander (2.7%), Mayhew et al. (2.5%), Poliquin (2.5%) and Wathen (2.5%). Therefore, the Brown, Epley, Poliquin and Wathen prediction methods now exhibited the smallest values for the affected limbs, while the Brown, Epley, Mayhew et al., Poliquin and Wathen prediction methods exhibited the smallest values for the control limbs.

In the affected limbs, the total errors of measurement for the more accurate prediction methods changed as follows: Brown (2.5%), Brzycki (2.5%), Epley (2.4%), Lander (2.4%), Mayhew et al. (2.5%), Poliquin (2.5%) and Wathen (2.6%). In the control limbs, the total errors for the more accurate prediction methods changed as follows: Brown (2.9%), Brzycki (2.8%), Epley (2.5%), Lander (2.6%), Mayhew et al. (2.7%), Poliquin (2.4%) and Wathen (2.4%). Therefore, the Epley and Lander equations now exhibited the smallest total error for the affected limbs, while the Poliquin and Wathen prediction methods exhibited the smallest total error for the control limbs.

In summary, the Brown, Brzycki, Epley, Lander, Mayhew et al., Poliquin and Wathen prediction methods exhibited relatively low levels of bias and error when the knee OA group performed the knee extension exercise. In addition, these equations produced the greatest numbers of subjects within 5% or less of their actual 1-RM performance (ranges: affected limbs 75-92%; control limbs 75-92%). In contrast, the Adams, Berger, KLW, Lombardi and O'Connor equations exhibited higher levels of bias and error for both the affected and control limbs. In addition, these equations produced the fewest subjects within 5% or less of their actual 1-RM performance (ranges: affected limbs 33-58%; control limbs 25-50%).

4.3.2.2. Leg press for Knee OA Subjects

The mean group values for predicted and actual 1-RM performance for the affected and control limbs are displayed in Table 4.12. The mean values for actual leg press 1-RM performance were 58.7 kg (SD 25.9) for the affected limbs and 65.3 kg (SD 30.2) for the control limbs. These values were significantly different ($p < 0.05$). The

Table 4.12: Leg Press Actual and Predicted 1-RM Results

1-RM Method	Affected Limb Maximal Strength in kg (mean ± SD)	Control Limb Maximal Strength in kg (mean ± SD)
Actual 1-RM	58.7 ± 25.9	65.3 ± 30.2
Adams	59.7 ± 28.4	66.2 ± 32.1
Berger	60.2 ± 28.7	66.9 ± 32.4
Brown	62.5 ± 29.8	69.4 ± 33.6
Brzycki	62.5 ± 29.8	69.7 ± 33.8
Epley	63.3 ± 30.2	70.3 ± 34.1
KLW	58.3 ± 27.8	64.7 ± 31.3
Lander	62.9 ± 30.0	70.1 ± 34.0
Lombardi	61.4 ± 29.2	67.7 ± 32.8
Mayhew et al.	63.1 ± 30.6	69.8 ± 33.8
O'Connor	60.0 ± 28.6	66.5 ± 32.2
Poliquin	63.8 ± 30.4	70.9 ± 34.4
Wathen	63.9 ± 30.6	71.1 ± 34.5

predicted leg press 1-RM values for the affected limbs ranged from 58.3 kg (27.8 SD) for the KLW equation to 63.9 kg (30.6 SD) for the Wathen equation. The predicted 1-RM values for the control limbs ranged from 64.7 kg (31.3 SD) for the KLW equation to 71.1 kg (34.5 SD) for the Wathen equation. The results of the paired t-tests using the percentage difference scores demonstrated that there were no significant differences in predictive accuracy across the control and affected limbs for any of the prediction methods ($p > 0.05$).

Bland and Altman graphs were plotted to give an appreciation of the bias for each of the prediction methods (see Figures 4.7 and 4.8). The bias, limits of agreement, ICCs, typical errors, typical errors as COVs, total errors of measurement and numbers of subjects within 5% of their true 1-RM are shown in Tables 4.13 and 4.14.

The Bland and Altman graphs show a random scatter of data for all of the prediction methods indicating that there were no systematic changes in error across the range of values. However, the results displayed in Figures 4.7 and 4.8 and in Tables 4.13 and 4.14 indicate that some prediction methods had a greater bias than others. In the affected limbs, the Brown, Brzycki, Epley, Lander, Mayhew et al., Poliquin and Wathen prediction methods exhibited greater bias (range: 3.8 to 5.3 kg) than the Adams, Berger, KLW, Lombardi and O'Connor equations (range: -0.4 to 2.7 kg). In the control limbs, the former prediction methods again exhibited greater bias (range: 4.1 to 5.8 kg) than the latter equations (range: -0.6 to 2.4 kg). The lowest levels of bias were produced by the KLW equation in both the affected and control limbs (-0.4 kg and -0.6 kg, respectively).

With respect to the 95% limits of agreement from the Bland and Altman analysis, the KLW equation exhibited the smallest interval for both the affected limbs (-11.4 to 10.6 kg) and control limbs (-12.2 to 11.0 kg). However, the Adams, Berger, Lombardi and O'Connor equations also produced similar intervals in both limbs.

Intraclass correlation coefficients were found to be high across all of the equations (range: 0.95 to 0.98 for the affected limbs and 0.96 to 0.98 for the control limbs). However, differences were observed in the lower bound confidence intervals. In the affected limbs, the Brzycki, Brown, Epley, Lander, Mayhew et al., Poliquin and Wathen prediction methods produced the lowest values (range: 0.80 to 0.88), while

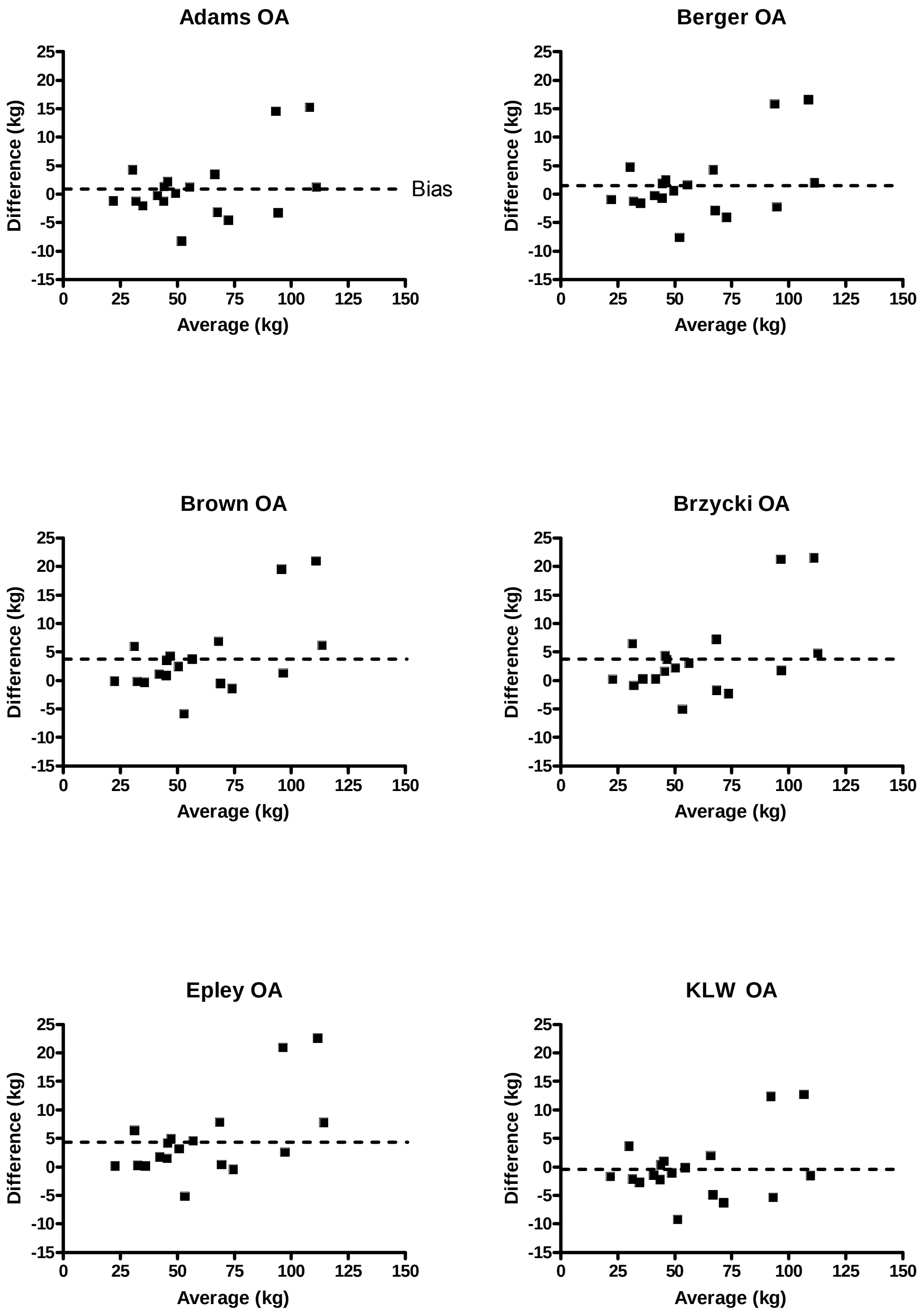

Figure 4.7: Bland and Altman Graphs for the Affected Limbs of Knee OA Subjects Performing the Leg Press Exercise

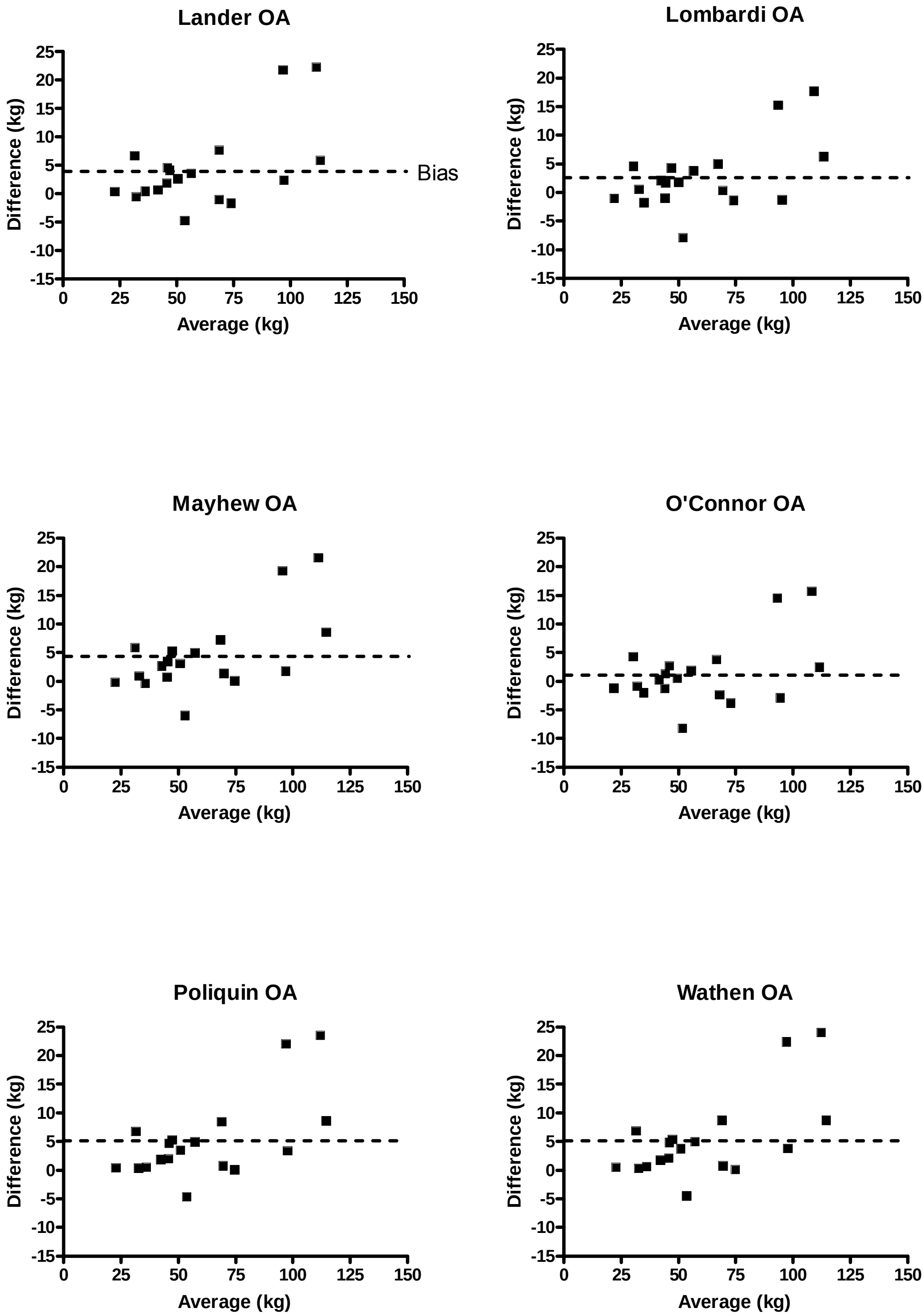

Figure 4.7 Continued: Bland and Altman Graphs for the Affected Limbs of Knee OA Subjects Performing the Leg Press Exercise

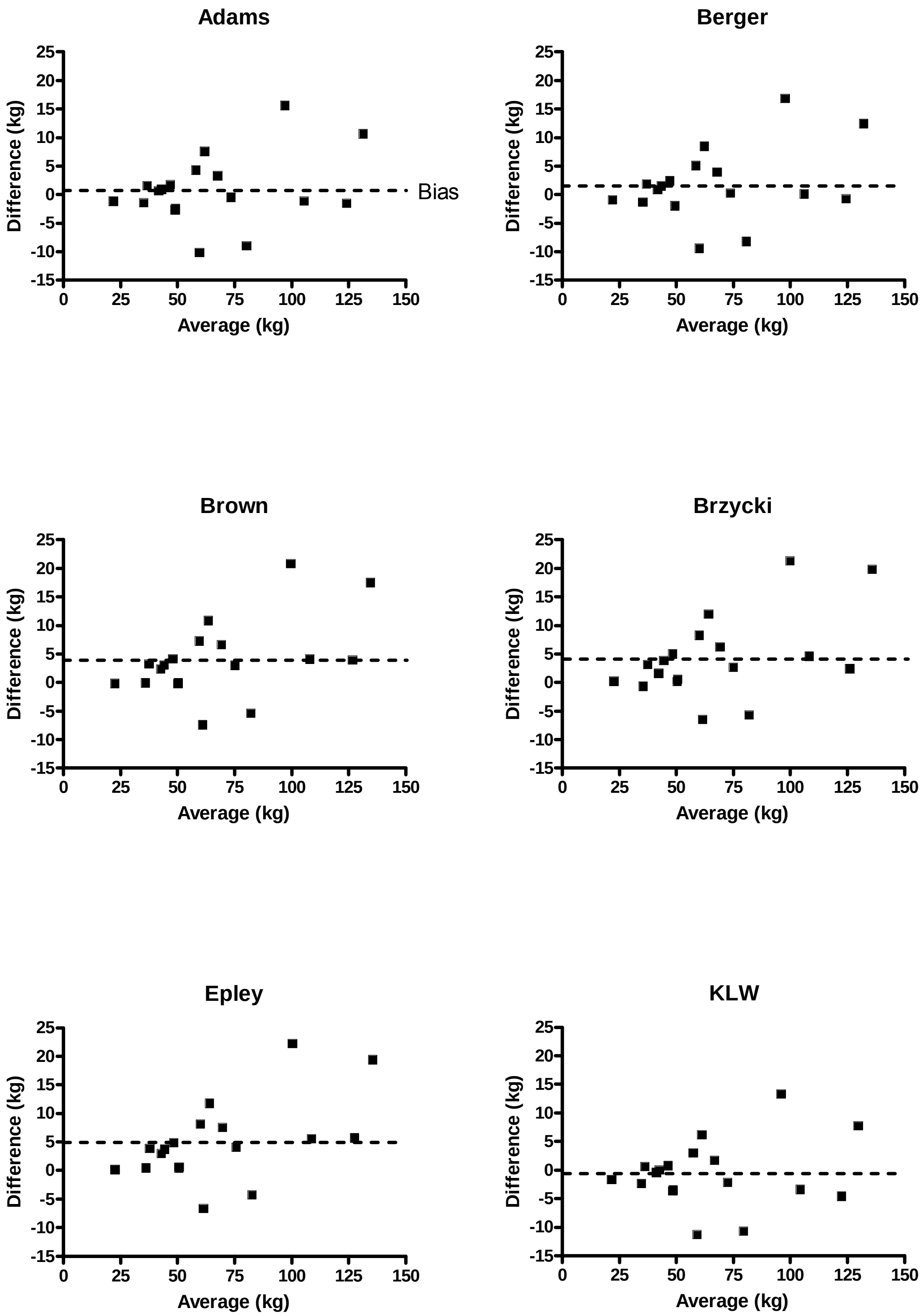

Figure 4.8: Bland and Altman Graphs for the Control Limbs of Knee OA Subjects Performing the Leg Press Exercise

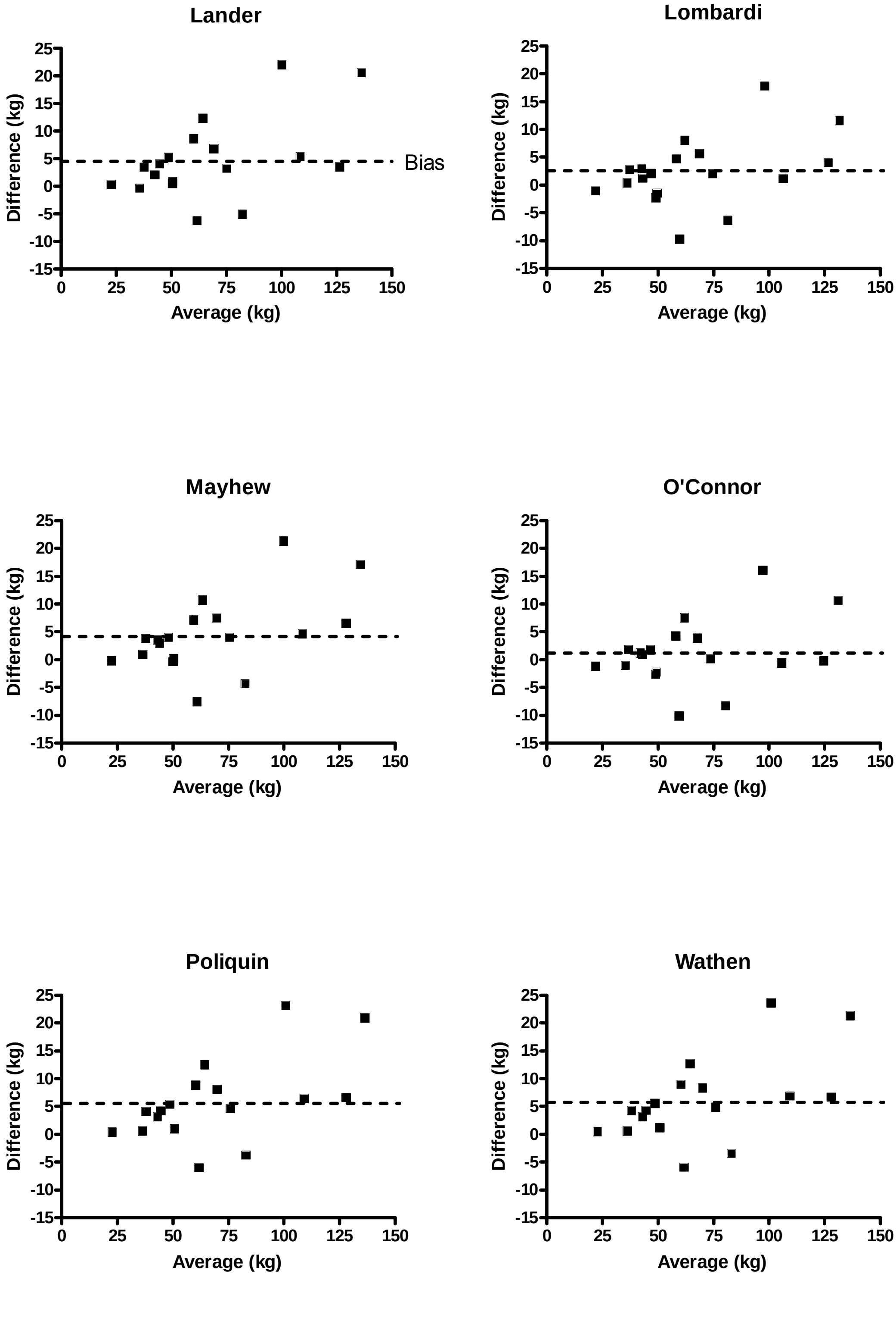

Figure 4.8 Continued: Bland and Altman Graphs for the Control Limbs of Knee OA Subjects Performing the Leg Press Exercise

Table 4.13: Statistical Analyses for the Affected Limbs of Knee OA Subjects Performing the Leg Press Exercise

Prediction Method	Bias (kg)	SD of Bias (kg)	95% Limits of Agreement	ICC	Lower Bound Confidence Interval	Typical Error (kg)	Typical Error as a Coefficient of Variation	95% Confidence Interval	Total Error	Subjects Within 5% of True 1-RM
Adams	1.0	5.9	-10.5 to 12.5	.98	.94	4.1	5.9%	4.6 to 8.4%	5.8%	12/18 (67%)
Berger	1.6	6.1	-10.4 to 13.5	.98	.94	4.3	6.0%	4.7 to 8.5%	5.9%	12/18 (67%)
Brown	3.8	6.8	-9.4 to 17.0	.96	.88	4.8	6.0%	4.7 to 8.5%	7.0%	9/18 (50%)
Brzycki	3.8	7.1	-10.1 to 17.7	.96	.88	5.0	6.3%	4.9 to 8.9%	7.2%	10/18 (56%)
Epley	4.6	7.0	-9.1 to 18.4	.96	.84	5.0	6.0%	4.7 to 8.5%	7.5%	8/18 (44%)
KLW	-0.4	5.6	-11.4 to 10.6	.98	.95	4.0	5.9%	4.6 to 8.4%	5.9%	8/18 (44%)
Lander	4.3	7.2	-9.8 to 18.3	.96	.86	5.1	6.2%	4.9 to 8.8%	7.5%	10/18 (56%)
Lombardi	2.7	6.0	-9.1 to 14.5	.97	.92	4.2	5.9%	4.6 to 8.3%	6.2%	10/18 (56%)
Mayhew et al.	4.5	6.7	-8.7 to 17.6	.96	.85	4.7	5.9%	4.6 to 8.3%	7.3%	7/18 (39%)
O'Connor	1.4	5.8	-10.1 to 12.8	.98	.94	4.1	5.9%	4.6 to 8.3%	5.8%	11/18 (61%)
Poliquin	5.1	7.2	-9.0 to 19.3	.95	.81	5.1	6.0%	4.7 to 8.5%	8.0%	8/18 (44%)
Wathen	5.3	7.3	-9.1 to 19.6	.95	.80	5.2	6.1%	4.7 to 8.6%	8.1%	8/18 (44%)

SD = Standard deviation, ICC = Intraclass correlation coefficients

Table 4.14: Statistical Analyses for the Control Limbs of Knee OA Subjects Performing the Leg Press Exercise

Prediction Method	Bias (kg)	SD of Bias (kg)	95% Limits of Agreement	ICC	Lower Bound Confidence Interval	Typical Error (kg)	Typical Error as a Coefficient of Variation	95% Confidence Interval	Total Error	Subjects Within 5% of True 1-RM
Adams	0.9	6.1	-11.1 to 12.9	.98	.95	4.3	5.9%	4.6 to 8.3%	5.7%	12/18 (67%)
Berger	1.6	6.3	-10.8 to 14.0	.98	.95	4.5	5.9%	4.6 to 8.4%	5.8%	11/18 (61%)
Brown	4.1	7.0	-9.5 to 17.7	.97	.90	4.9	5.9%	4.6 to 8.4%	6.9%	7/18 (39%)
Brzycki	4.4	7.3	-10.0 to 18.7	.97	.89	5.2	6.1%	4.8 to 8.6%	7.2%	8/18 (44%)
Epley	5.0	7.2	-9.1 to 19.1	.97	.86	5.1	5.9%	4.6 to 8.4%	7.5%	8/18 (44%)
KLW	-0.6	5.9	-12.2 to 11.0	.98	.95	4.2	5.9%	4.6 to 8.3%	5.9%	9/18 (50%)
Lander	4.8	7.4	-9.7 to 19.4	.96	.87	5.2	6.1%	4.7 to 8.6%	7.5%	8/18 (44%)
Lombardi	2.4	6.2	-9.8 to 14.6	.98	.94	4.4	5.9%	4.6 to 8.3%	6.0%	9/18 (50%)
Mayhew et al.	4.5	6.9	-9.0 to 18.0	.97	.88	4.9	5.8%	4.6 to 8.3%	7.1%	8/18 (44%)
O'Connor	1.2	6.1	-10.8 to 13.1	.98	.95	4.3	5.8%	4.6 to 8.3%	5.7%	11/18 (61%)
Poliquin	5.6	7.4	-9.0 to 20.2	.96	.82	5.3	5.9%	4.6 to 8.4%	7.9%	6/18 (33%)
Wathen	5.8	7.5	-8.9 to 20.5	.96	.81	5.3	5.9%	4.6 to 8.4%	8.1%	6/18 (33%)

SD = Standard deviation, ICC = Intraclass correlation coefficients

the Adams, Berger, KLW, Lombardi and O'Connor equations produced the highest values (range: 0.92 to 0.95). In the control limbs, the former prediction methods again produced the lowest values (range: 0.81 to 0.90), while the latter equations produced the highest values (range: 0.94 to 0.95).

Typical errors for the prediction methods were relatively high for the knee OA group when performing the leg press exercise. In the affected limbs, the largest typical error was observed for the Wathen equation (5.2 kg), while the smallest typical error was observed for the KLW equation (4.0 kg). In the control limbs, the largest typical error was observed for the Wathen equation (5.3 kg), while the smallest typical error was observed for the KLW equation (4.2 kg).

The typical errors as COVs tended to be larger when the knee OA group performed the leg press exercise. In the affected limbs, the highest value was observed for the Brzycki equation (6.3%), while the lowest value was observed for the Adams, KLW, Lombardi, Mayhew et al. and O'Connor equations (5.9%). In the control limbs, the highest value was observed for the Brzycki and Lander equations (6.1%), while the lowest value was observed for the Mayhew et al. and O'Connor equations (5.8%).

The total errors of measurement were also comparatively high when the knee OA group performed the leg press exercise. In the affected limbs, the greatest total error was observed for the Wathen equation (8.1%), while the smallest total error was observed for the Adams and O'Connor equations (5.8%). In the control limbs, the greatest total error was observed for the Wathen equation (8.1%), while the smallest total error was observed for the Adams and O'Connor equation (5.7%).

The number of subjects with predicted 1-RM values within 5% of their true 1-RM values differed across the prediction equations. In the affected limbs, the Adams and Berger equations produced the greatest number of subjects with predicted 1-RM values within 5% of their true 1-RM (67%), while the Mayhew et al. equation produced the fewest (39%). In the control limbs, the Adams equation produced the greatest number of subjects within 5% of their true 1-RM (67%), while the Poliquin and Wathen methods produced the fewest (33%).

In summary, all of the prediction methods demonstrated relatively high levels of bias and error when the knee OA group performed the leg press exercise. However, of these methods, the Adams, Berger, KLW, Lombardi and O'Connor equations generally demonstrated lower error levels in both the affected (range: bias -0.4 to 2.7 kg; typical error as a COV 5.9-6.0%; total error 5.8-6.2%) and control limbs (range: bias -0.6 to 2.4 kg; typical error as a COV 5.8-5.9%; total error 5.7-6.0%). In addition, the Adams, Berger and O'Connor equations produced the greatest numbers of subjects within 5% or less of their actual 1-RM performance (range: affected and control limbs 61-67%). In contrast, the Brown, Brzycki, Epley, Lander, Mayhew et al., Poliquin and Wathen methods exhibited higer levels of bias and error in both the affected (range: bias 3.8 to 5.3 kg; typical error as a COV 5.9-6.3%; total error 7.0-8.1%) and control (range: bias 4.1 to 5.8 kg; typical error as a COV 5.8-6.1%; total error 6.9-8.1%) limbs. In addition, these equations generally produced the fewest subjects within 5% or less of their actual 1-RM performance (ranges: affected limbs 39-56%; control limbs 33-44%).

5. CHAPTER 5: DISCUSSION

5.1. INTRODUCTION

This chapter is divided into four main sections. The first section compares the demographics and injury/OA characteristics for each group to data from the literature. The second section discusses the primary aim of this study which was to evaluate the accuracy of prediction methods when used to estimate knee extension and leg press 1-RM performance in individuals with knee injuries and knee OA. The third section describes the practical implications of this study, while the final section presents the limitations of the study.

5.2. SUBJECTS

The mean age, height and weight of the knee injured subjects in the current study (33.15 years, 1.75 m, 75.91 kg) were comparable to those of subjects in ACL and meniscus studies by Moffet et al. (1998), (41.3 years, 1.74 m, 80.7 kg); Benjuya, Plotqin & Melzer (2000), (31 years, 1.75 m, 74 kg); and St Clair Gibson et al. (2000), (males: 38.3 years, 1.76 m, 80.1 kg; females: 31.5 years, 1.66 m, 60.3 kg).

The time from injury to strength testing in the current study ranged from 6-300 months with a mean interval of 81.0 months (SD 89.4). This is comparable to the mean intervals between injury and strength testing reported by Moffet et al. (1998), Benjuya, Plotqin & Melzer (2000) and St Clair Gibson et al. (2000) which ranged from approximately nine months to 15 years.

Of the knee injured subjects in the current study, ten (50%) had ACL injuries, seven (35%) had medial meniscus injuries, four (20%) had lateral meniscus injuries and two had PCL injuries (10%), although some were combined injuries. A similar prevalence of these injuries was reported by Majewski, Susanne, & Klaus (2006) for a group of 3482 subjects with sport related internal knee injuries. Among these internal knee injuries, the authors stated that 45.4% were ACL injuries, 24% were medial meniscus injuries, 8.2% were lateral meniscus injuries and 1.5% were PCL injuries.

Finally, seven of the ACL injured subjects in the current study were males, while three were females. This ratio was contrary to the findings of a number of studies which have suggested that ACL injuries occur more frequently in females than in males (Dugan, 2005; Gwinn, Wilckens, McDevitt, Ross, & Kao, 2000).

The mean height and weight of the knee OA subjects in the current study (1.72 m, 78.43 kg) were comparable to those of knee OA subjects in studies by Hurley et al. (1997), (n = 103, 60.73 years, 1.65 m, 76.95 kg); Hassan et al. (2001), (n = 77, 63.4 years, 1.65 m, 83.4 kg); and Molloy (2005), (n = 26, 63.6 years, 1.64 m, 73.8 kg); all of which used similar inclusion criteria. However, the knee OA subjects in the current study were somewhat younger (57.44 years) than the subjects in these studies.

The mean WOMAC score for the knee OA subjects in the current study was 28.1 (range: 0-87.6) out of a possible score of 240. This represents a mean of 12% of the total possible score. This value was appreciably lower than the WOMAC scores reported in a number of studies. For example, Hassan et al. (2001) reported a median WOMAC score of 51/96, representing 53% of the total possible score. In addition, Molloy (2005) reported a mean WOMAC score of 51.85/240, representing 21% of the total possible score. This suggests that the knee OA subjects in the current study were functioning at a higher level compared to other studies. However, in a recent study Hall, Mockett, & Doherty (2006) reported a mean WOMAC score of 40/96 (42% of total possible score) for subjects with knee OA and knee pain and a mean WOMAC score of 12/96 (13% of total possible score) for subjects with knee OA and minimal or no pain. As a number of subjects in the current study had low pain levels at the time of completing the WOMAC, it appears that this group was similar to the asymptomatic knee OA group in the Hall, Mockett, & Doherty (2006) study.

5.3. ACCURACY OF THE PREDICTION METHODS

The current study is the first to evaluate the accuracy of 1-RM prediction methods in subjects with knee injuries or knee OA. There is very limited information available concerning the use of such equations when assessing strength in individuals with pathological conditions. A recent study (Lovelace, 2005) investigated the accuracy of 1-RM prediction equations in individuals following plantarflexor unit injuries using very similar methods to the current study. Thus, the findings from the current study can be closely compared to those of Lovelace (2005) to provide some evidence as to whether the same equations might be used across these different injuries.

A discussion regarding the accuracy of the prediction methods when used to estimate knee extension and leg press 1-RM performance is presented below. The first section relates to the knee injury group, while the second section relates to the knee OA group. The third section compares the accuracy of the prediction methods across the knee injury and knee OA groups. The final section compares the accuracy of the prediction methods across the knee extension and leg press exercises.

5.3.1. Knee Injury Subjects

5.3.1.1. Knee Extension for the Knee Injury Subjects

Actual knee extension 1-RM values were greater in the control limbs than in the affected limbs for the knee injury group. This difference represented a mean quadriceps deficit of 7.0% for the affected limbs. This value was similar to the side-to-side deficits reported by Arangio et al. (1997), (8.3-12.9%); Järvelä et al. (2002), (4.5-10.3%); Keays et al. (2003), (7.3-12%); and Mattacola et al. (2002), (6.4-15.4%) for ACL injured subjects. However, this value was considerably lower than the deficits reported in other ACL and meniscal studies (range: 17.6-38%) (Moffet et al., 1998; St Clair Gibson et al., 2000; Strauss et al., 1998). The relatively small mean knee extension strength deficit observed in the current study may have occurred because some subjects had participated in unilateral strengthening programmes that resulted in greater maximal strength in their affected limbs, compared to their control limbs. In addition, the mean time since injury was 81.0 (SD 89.4) months and many subjects had minimal complaint of pain at the time of testing.

No significant differences in predictive accuracy across the control and affected limbs were found for the Adams, Berger, Brown, Epley, KLW, Lombardi, Mayhew et al., O'Connor and Poliquin prediction methods ($p > 0.05$). However, predictive accuracy across the control and affected limbs was significantly different ($p < 0.05$) for the

Brzycki and Lander equations and approached statistical significance for the Wathen equation ($p = 0.057$). All three of these equations exhibited greater mean underestimations of 1-RM performance in the control limbs compared to the affected limbs. However, two subjects contributed considerably to these findings. The first subject was identified as an outlier with mean percentage differences between predicted and actual 1-RM performance of -17.2% in the control limb and -13.6% in the affected limb. The reason for these differences is unclear. Although this subject had a notable weight training background, his level of training did not appear to be significantly different from that of other resistance trained subjects in the group. The second subject was identified as having much larger differences in predictive accuracy across the control and affected limbs compared to all of the other participants (mean percentage differences between predicted and actual 1-RM performance of -13.9% in the control limb and 0.6% in the affected limb). It is also unclear why this subject exhibited such a large difference in predictive accuracy across the control and affected limbs, as she had not trained with weights and had not participated in any limb dominant sports. When the data from these subjects were removed, there were no longer significant differences in predictive accuracy across the control and affected limbs for any of the equations. In turn, this suggests that the accuracy of each 1-RM equation was similar whether used for the affected or control limbs. These findings concur with those of Lovelace (2005) who found no significant differences ($p > 0.05$) in predictive accuracy across injured and control limbs for eight 1-RM equations.

High intraclass coefficients (ICC) were observed for all the prediction methods across both limbs (range: 0.92 to 0.99). However, large differences were observed in the lower bound confidence intervals. The Adams, Berger, KLW, Lombardi and O'Connor equations produced the lowest values in the affected (range: 0.25 to 0.89) and control (range: 0.08 to 0.71) limbs. In contrast, the Brown, Brzycki, Epley, Lander, Mayhew et al., Poliquin and Wathen prediction methods produced the highest values in the affected (range: 0.96 to 0.98) and control (range: 0.86 to 0.95) limbs. Therefore, the lower bound confidence intervals for the latter prediction methods support their use when estimating knee extension 1-RM performance in individuals following knee injuries. Only recent studies by Taylor & Brandy (2005) and Lovelace (2005) have also reported ICCs for generic prediction equations. Taylor & Brandy

(2005) investigated the accuracy of the Brzycki equation when estimating 1-RM performance in two different positions for shoulder internal rotation. They reported that predicted and actual shoulder internal rotation 1-RM values had ICCs of 0.99 (95% CI = 0.98 to 0.99) in the first position and 0.97 (95% CI = 0.92 to 0.99) in the second position. Lovelace (2005) reported that high ICCs were observed for eight 1-RM prediction equations across both the affected and control limbs of subjects with plantarflexor unit injuries (range: 0.955 to 0.988). However, the author also noted differences in the lower bound confidence intervals. These values were higher for the Brzycki, Epley, Lander and Lombardi equations (range: affected limbs 0.910 to 0.961; control limbs 0.917 to 0.972), than for the Mayhew et al., O'Connor, Poliquin and Wathen prediction methods (range: affected limbs 0.782 to 0.854; control limbs 0.783 to 0.884). Thus, while the lower bound confidence intervals for the Poliquin and Wathen equations were high in the current study for a knee extension exercise, they were relatively low in the Lovelace study for a calf raise exercise. This suggests the accuracy of these equations may differ for these exercises.

While high correlation coefficients may provide an indication of "relative reliability" (Atkinson & Nevill, 1998), it has been suggested that statistical procedures such as Bland and Altman analysis, typical error and the total error of measurement should be utilized when attempting to assess the level of agreement between two methods of clinical measurement (Atkinson & Nevill, 1998; Bland & Altman, 1986; Hopkins, 2000). Therefore, these analyses were also performed in the current study.

The random scatter of data observed in the Bland and Altman graphs suggested that the differences between predicted and actual 1-RM performance were relatively consistent over the range of loads lifted. Lovelace (2005) reported a similar finding for eight prediction equations when subjects with plantarflexor unit injuries performed a calf raise exercise. However, in the current study, the bias values were greater across both limbs for the Adams, Berger, KLW, Lombardi and O'Connor equations (-11.9 to -4.5 kg), compared to the Brown, Brzycki, Epley, Lander, Mayhew et al., Poliquin and Wathen prediction methods (-5.2 to -0.2 kg). These findings suggest that the former equations consistently underpredicted knee extension 1-RM performance to a greater degree than the latter prediction methods. This difference between the equations is not surprising considering that, in the 5-10 RTF range, the Adams, Berger, KLW, Lombardi and O'Connor equations generally use greater percentages of 1-RM at the same number of RTFs to estimate 1-RM performance (see Table 2.7). However, it appears that the same two subjects described earlier in this section also had a considerable impact on the observed bias values. When the data from these individuals were excluded from the analyses, the level of bias in the affected limbs for the more accurate prediction methods changed as follows: Epley (-0.5 kg), Lander (-1.0 kg), Mayhew et al. (-0.9 kg), Poliquin (0.3 kg) and Wathen (0.6 kg). In the control limbs, the bias for the more accurate prediction methods changed as follows: Epley (-2.1 kg), Lander (-2.9 kg), Mayhew et al. (-2.3 kg), Poliquin (-1.3 kg) and Wathen (-1.0 kg). Importantly, these bias values were all within 3% of the actual 1-RM scores across both limbs. Lovelace (2005) also reported bias values within 3% of actual 1-RM performance for eight 1-RM prediction equations. However, it appears that although the Poliquin and Wathen prediction methods exhibited the lowest levels of bias in the current study, they exhibited some of the highest levels of bias in the Lovelace study (Poliquin: affected 3.3 kg, control 4.1 kg; Wathen: affected 3.1 kg, control 4.3 kg). This finding again suggests that the accuracy of these equations may differ for knee extension and calf raise exercises. In summary, the bias values observed in the current study appear to provide the greatest support for the Poliquin and Wathen methods when predicting knee extension 1-RM performance in subjects with knee injuries.

The 95% LOA from the Bland and Altman analyses were relatively large for all the prediction methods across both limbs. The Mayhew et al. equation exhibited the smallest interval for both the affected (-11.3 to 8.0 kg; interval: 19.3 kg) and control limbs (-16.3 to 8.6 kg; interval: 24.9 kg). However, when data from the two subjects described earlier were excluded from the analyses, the 95% LOA intervals decreased for all of the prediction methods. In the affected limbs, the 95% LOA intervals for the more accurate Epley, Lander, Mayhew et al., Poliquin and Wathen prediction methods ranged from 11.4 to 13.0 kg. In the control limbs, the 95% LOA intervals for these methods now ranged from 14.8 to 16.1 kg. Using the Poliquin prediction method as an example, the results of the current study (n = 18 after the removal of the atypical subject's data) suggest that if the affected limb of another individual was tested, there is a 95% probability that their predicted 1-RM would be between 5.8 kg below and 6.4 kg above their actual 1-RM scores. Based on the mean actual 1-RM value of 100.4 kg observed in the current study, these values would represent a range extending from a 5.8% underprediction to a 6.4% overprediction of actual 1-RM performance. Lovelace (2005) also reported 95% LOA values for eight prediction equations. In the affected limbs, the Lander equation exhibited the smallest interval (-7.09 to 7.27 kg). Based on the mean actual calf raise 1-RM value reported for the affected limbs (131.37 kg), this would represent a range extending from a 5.4% underprediction to a 5.5% overprediction. Thus, in percentage terms, the 95% LOA values were similar between these studies for the more accurate equations.

In the current study, typical errors ranged from 3.5 to 4.2 kg in the affected limbs and from 4.5 to 5.1 kg in the control limbs. When converted to typical errors as COVs, the values ranged from 3.1 to 3.2% in the affected limbs and from 3.8 to 4.0% in the control limbs. These values suggest that random error was low across the two testing procedures. However, the total error of measurement values demonstrated more variability. Total errors were greatest for the Adams, Berger, KLW, Lombardi and O'Connor equations in the affected (range: 4.7-7.7%) and control (range: 6.0-9.5%) limbs. In contrast, total errors were lower for the Brown, Brzycki, Epley, Lander, Mayhew et al., Poliquin and Wathen prediction methods in the affected (range: 3.0-3.6%) and control (range: 4.2-5.3%) limbs. These findings suggest that the mean values for actual and predicted 1-RM performance differed considerably for some equations, with Adams, Berger, KLW, Lombardi and O'Connor equations consistently underestimating knee extension 1-RM performance to a greater degree than the other prediction methods. However, when data from the two subjects described earlier were excluded from the analyses, the levels of error decreased for all of the prediction methods. For the more accurate Epley, Lander, Mayhew et al., Poliquin and Wathen prediction methods, the typical errors as COVs ranged from 2.4 to 2.6% in the affected limbs and from 2.7 to 2.8% in the control limbs, while the total errors ranged from 2.4 to 2.8% in the affected limbs and from 2.8 to 3.5% in the control limbs. Importantly, Lovelace (2005) also reported typical errors as COVs for eight 1-RM prediction methods. These values ranged from 1.7 to 2.9% across both limbs, which is similar to the ranges observed in the current study.

Other studies investigating the accuracy of 1-RM prediction equations have described a variety of error statistics including the standard error of the estimate (SEE), average error and different forms of total error. It should be recognized that the terminology and calculations used for these error statistics are not always consistent across different studies. Therefore, these statistics may not always be directly comparable, although they may all provide some indication of predictive accuracy when estimating 1-RM performance from a prediction equation. Using various error statistics, some studies have reported error rates of less than 5% for existing generic 1-RM prediction equations (Cummings & Finn, 1998; Mayhew, Kerksick et al., 2004; Mayhew, Prinster et al., 1995; Mayhew et al., 2002; Whisenant et al., 2003). However, it should be noted that all of these studies examined the free-weight bench press exercise which was used in the development of most, if not all, of the generic 1-RM prediction equations being investigated. In contrast, studies examining other exercises have reported much higher error rates, especially for some lower extremity exercises (Knutzen et al., 1999; LeSuer et al., 1997; Wood et al., 2002).

With respect to knee extension 1-RM performance, it appears that only one study has investigated the accuracy of generic prediction equations. In a study examining older sedentary adults (n = 49), Wood, Maddalozzo, & Harter (2002) reported average error expressed as a percentage of mean 1-RM for seven prediction equations when estimating knee extension 1-RM performance. Over the full range of repetitions to failure (RTFs) the authors reported error rates of 22 to 26% for the Brzycki, Epley, Lander, Lombardi, Mayhew et al., O'Connor and Wathen equations. However, when the analysis was performed only on subjects who performed RTFs ≤ 10 (n = 31) the range of error rates for these seven equations reduced to 17 to 20%.

Three other studies have used the knee extension exercise to develop 1-RM prediction equations. Braith, Graves, Leggett, & Pollock (1993) developed prediction equations for the knee extension exercise before and after 18 weeks of resistance training using the weight lifted for a 7-10 RTF range. From the pre-training data (n = 58), the authors developed a 1-RM prediction equation which had a SEE of 9.3 kg (10.6% of the mean 1-RM value). From the post-training data (n = 47), the authors developed a 1-RM prediction equation which had a SEE of 9.9 kg (8.9% of the mean 1-RM value). Abadie & Wentworth (2000) also developed a prediction equation for the knee extension exercise but used the weight lifted for a 5-10 RTF range (n = 30). The authors reported the equation had a SEE of 2.3 kg (6.9% of the mean 1-RM value).

Finally, Dohoney, Chromiak, Lemire, Abadie, & Kovacs (2002) developed two prediction equations for the knee extension exercise using the weight lifted for a 4-6 RTF range and the weight lifted for a 7-10 RTF range (n = 34). The authors reported a SEE of 11.9 kg (8.4% of the mean 1-RM value) for the 4-6 RTF equation and a SEE of 13.7 kg (9.7% of the mean 1-RM value) for the 7-10 RTF equation.

Although not directly comparable, the results from the studies described above suggest that higher error rates occurred in these investigations when compared to the current study. This is somewhat surprising considering that three of the studies developed equations specifically for the knee extension exercise, while the current study examined generic prediction equations. However, five main factors may explain these differences in error rates. Firstly, it should be noted that the three studies which developed equations for the knee extension exercise simply used the load lifted over a range of RTFs to predict 1-RM performance. Since the loads lifted across a range of 3 repetitions or more are likely to vary considerably, this could increase the levels of predictive error for these equations. In contrast, generic 1-RM prediction equations utilize both the sub-maximal load lifted and the exact number of RTFs performed at that load to estimate maximal strength. Secondly, RTFs were limited to ten repetitions or less in the current study because previous studies have demonstrated that this range improves the accuracy of 1-RM prediction equations. Thirdly, a strict methodology for performing the knee extension exercise was followed in the current study, with a particular emphasis on achieving full available knee extension for every repetition. Fourthly, the knee extension exercise was performed bilaterally in the other studies but unilaterally in the current study. Finally, it is possible that differences in subject characteristics between the studies may have influenced the error rates. For example, the current study used a sample consisting of 14 males and six females (mean age 33.2 ± 9.9 years; range 20-54 years), of which seven males and one female had a recent history of weight training. In contrast, the Wood, Maddalozzo, & Harter (2002) study used a sample of older untrained adults consisting of 26 males and 23 females (mean age 53.55 ± 3.34 years), the Abadie & Wentworth (2000) study used a sample of untrained younger females (mean age 22.2 ± 1.2 years), the Dohoney, Chromiak, Lemire, Abadie, & Kovacs (2002) study used a sample of untrained younger males (mean age 23.2 ± 3.2 years) and the Braith, Graves, Leggett, & Pollock (1993) study used a sample consisting of 33 men and 25 women (mean age 25 ± 5 years) who were initially untrained. However, it has generally been demonstrated that the accuracy of 1-RM prediction equations does not vary significantly across different age groups or genders (Knutzen et al., 1999; Mayhew, Kerksick et al., 2004; Reynolds et al., 2006; Whisenant et al., 2003; Wood et al., 2002). In addition, the results of some studies have actually suggested that generic 1-RM prediction equations may be more accurate for untrained subjects than for trained subjects (Braith et al., 1993; Hoeger et al., 1987; Hoeger et al., 1990; Pick & Becque, 2000). Therefore, it seems unlikely that differences in subject characteristics could explain why lower error rates were observed in the current investigation compared to previous studies.

The number of subjects with predicted 1-RM values within 5% of their true 1-RM values differed greatly across the prediction equations. In the affected limbs, the Brzycki, Epley and Lander equations (17/20 or 85%) and the Brown, Mayhew et al., Poliquin and Wathen prediction methods (16/20 or 80%) produced the greatest number of subjects within 5% of their true 1-RM. In contrast, the Adams, Berger, KLW, Lombardi and O'Connor equations produced the fewest (range: 2/20 to 12/20). In the control limbs, the Poliquin and Wathen prediction methods (15/20 or 75%) produced the greatest number of subjects with predicted 1-RM values within 5% of their true 1-RM. In contrast, the Adams, Berger, Brown, Brzycki, Epley, KLW, Lander, Lombardi, Mayhew et al. and O'Connor equations produced the fewest (range: 2/20 to 14/20). Other studies have also examined how frequently predicted 1-RM values fell within a predetermined range of actual 1-RM performance. For example, Mayhew et al. (1999) reported that when using a NFL 225 bench press test prediction equation, 68% of a cross-validation sample (n=28) had predicted 1 RM values within ± 10 lb of their actual 1 RM performance (group mean 1-RM: 291.8 lbs ± 46.7). In another study investigating the NFL 225 bench press test (n = 260), Mayhew, Ware, et al. (2002) reported that the Brzycki (34%), Epley (53%), Lander (37%), Mayhew et al. (37%) and Wathen (46%) equations produced relatively low numbers of subjects within ± 4.5 kg of their actual 1-RM performance (group mean 1-RM: 136.7 kg ± 23.6). In a more recent study, Mayhew, Jaques, et al. (2004) also reported that the Epley (36.9%), Lombardi (38.5%), Mayhew et al. (54.6%) and Wathen (14.3%) equations produced relatively low numbers of subjects within ± 10 lb of their actual 1 RM performance (group mean 1-RM: 302.5 lbs ± 42.1). In contrast, Mayhew, Kerksick, et al. (2004) reported slightly higher numbers of subjects within ±

4.5 kg of actual bench press 1-RM values (group mean 1-RM: 87.8 kg ± 20.1) for the Adams (63%), Berger (63%), Brown (58%), Brzycki (58%), Epley (49%), Lander (56%), Lombardi (62%), Mayhew et al. (51%), O'Connor (64%) and Wathen (48%) equations. Therefore, the more accurate prediction equations in the current study (Poliquin and Wathen) appear to have produced a relatively high number of subjects within 5% of their actual 1–RM performance, when compared to previous investigations. However, since all of the previous studies used fixed weight values instead of percentage difference values, direct comparisons are not possible.

In summary, the Adams, Berger, KLW, Lombardi and O'Connor equations appeared to be relatively inaccurate when predicting knee extension 1-RM performance in both the affected limbs (ranges: lower bound ICCs 0.254 to 0.888, bias -9.2 kg to -4.5 kg, total error 4.7 to 7.7%, subjects within 5% of actual 1-RM 2/20 to 12/20) and the control limbs (ranges: lower bound ICCs 0.076 to 0.705, bias -11.9 kg to -6.6 kg, total error 6.0 to 9.5%, subjects within 5% of actual 1-RM 2/20 to 10/20) of subjects with knee injuries. In contrast, the Brown, Brzycki, Epley, Lander, Mayhew et al., Poliquin and Wathen prediction methods generally appeared to be relatively accurate when predicting knee extension 1-RM performance. However, while these more accurate equations produced similar 95% LOA, ICC, typical error and total error values, the Poliquin and Wathen equations demonstrated somewhat superior results with respect to bias and the number of subjects within 5% or less of actual 1-RM performance.

5.3.1.2. Leg Press for the Knee Injury Subjects

Actual leg press 1-RM values were not significantly different across the affected (87.3 kg, SD 28.4) and control (86.3 kg, SD 27.5) limbs for the knee injury group. The similarity in strength between the affected and control limbs during the leg press exercise may have been due to the recruitment of other muscle groups (e.g. gluteals and hamstrings) which were less inhibited by knee injury than the quadriceps muscle. In addition, some ACL injured subjects described apprehension and/or sensations of instability with the knee extension exercise that they did not experience with the leg press exercise.

High ICCs were observed for all the prediction methods across both limbs (range: 0.97 to 0.99). Importantly, these findings concur with those of Taylor and Bandy (2005) who reported ICCs of 0.97 to 0.99 for the Brzycki equation, and those of Lovelace (2005) who reported ICCs of 0.955 to 0.988 for eight prediction equations. However, in the current study differences were observed in the lower bound confidence intervals. In the affected limbs, all of the prediction methods produced relatively high values (range: 0.81 to 0.99). In contrast, the Epley, Mayhew et al., Poliquin and Wathen prediction methods produced lower values in the control limbs (range: 0.59 to 0.79), while the Adams, Berger, Brown, Brzycki, KLW, Lander, Lombardi and O'Connor equations produced higher values (range: 0.85 to 0.98). Therefore, it appears that other than the Epley, Mayhew et al., Poliquin and Wathen prediction methods, all of the equations exhibited high "relative reliability" when used to estimate leg press 1-RM performance in individuals following knee injuries.

The random scatter of data observed in the Bland and Altman graphs suggested that the differences between predicted and actual 1-RM performance were relatively consistent over the range of loads lifted. Lovelace (2005) reported a similar finding for eight prediction equations when subjects with plantarflexor unit injuries performed a calf raise exercise. However, in the current study, the bias values were greater across both limbs for the Brown, Brzycki, Epley, KLW, Lander, Mayhew et al., Poliquin and Wathen prediction methods (affected -3.1 to 4.6 kg; control -2.7 to 5.4 kg), than for the Adams, Berger, Lombardi and O'Connor equations (affected -1.1 to 1.5 kg; control -0.8 to 1.7 kg). These findings suggest that the former prediction methods tended to overpredict leg press 1-RM performance. This difference between the prediction methods occurred because, in the 5-10 RTF range, the Brown, Brzycki, Epley, Lander, Mayhew et al., Poliquin and Wathen prediction methods generally use lower percentages of 1-RM at the same number of repetitions to failure to estimate 1-RM performance (see Table 2.7). In contrast, the KLW equation tended to appreciably underpredict 1-RM performance because this equation uses the highest percentages of 1-RM to estimate 1-RM performance (see Table 2.7). Importantly, the bias values for the more accurate Adams, Berger, Lombardi and O'Connor equations were all within 3% of the actual 1-RM scores across both limbs. This corresponds to Lovelace's (2005) findings that the bias values for eight prediction equations fell within 3% of actual 1-RM performance. However, while Lovelace reported relatively low bias levels for the Lombardi equation (affected 1.31 kg; control 0.82 kg), they were higher for the O'Connor equation (affected -3.17 kg; control -3.71 kg).

With respect to the 95% LOA from the Bland and Altman analysis, the KLW equation exhibited the smallest intervals for the affected limbs (-9.2 to 3.0 kg, interval 12.2 kg) and the control limbs (-9.3 to 3.8 kg, interval 13.1 kg). However, the Adams, Berger, Lombardi and O'Connor equations also produced similar values in the affected limbs (interval range: 12.5 to 13.5 kg), while the Adams, Berger, and O'Connor equations produced similar values in the control limbs (interval range: 13.1 to 13.3 kg). Using the O'Connor equation as an example, the results of the current study (n = 19) suggest that if the affected limb of another individual was tested, there is a 95% probability that their predicted 1-RM would be between 6.8 kg below and 5.7 kg above their actual 1-RM scores. Based on the mean actual 1-RM value of 83.7 kg observed in the current study, these values would represent a range extending from an 8.1% underprediction to a 6.8% overprediction of actual 1-RM performance. Importantly, Lovelace (2005) reported that the Lander equation produced the smallest 95% LOA interval (-7.09 to 7.27 kg) when subjects with plantarflexor unit injuries performed a calf raise exercise. Based on the mean actual calf raise 1-RM value reported for the affected limbs, this would represent a range extending from a 5.4% underprediction to a 5.5% overprediction. Thus, in percentage terms, the 95% LOA values were slightly higher in the current study for the more accurate prediction equations. However, while the Lombardi and O'Connor equations had relatively small 95% LOA intervals in the current study, they produced the largest intervals in the affected limbs in the Lovelace study.

Typical errors ranged from 2.2 to 3.3 kg in the affected limbs and from 2.4 to 3.0 kg in the control limbs. When converted to typical errors as COVs, the values ranged from 2.8 to 3.8% in the affected limbs and from 2.9 to 3.5% in the control limbs. These values suggested that random error across the two testing procedures was low. In contrast, the total error of measurement values demonstrated more variability. Total errors were greatest for the Brown, Brzycki, Epley, KLW, Lander, Mayhew et al., Poliquin and Wathen prediction methods in the affected (range: 3.7-4.8%) and control (range: 3.8-5.3%) limbs. In contrast, total errors were lower for the Adams, Berger, Lombardi and O'Connor equations in the affected (range: 2.9-3.3%) and control (range: 2.9-3.2%) limbs. These findings suggested that the mean values for actual and predicted 1-RM performance differed more for some equations, with the Brown, Brzycki, Epley, Lander, Mayhew et al., Poliquin and Wathen prediction methods tending to overpredict knee extension 1-RM performance, while the KLW equation appreciably underestimated 1-RM performance. Importantly, Lovelace (2005) also reported typical errors as COVs for eight 1-RM prediction methods. These values ranged from 1.7 to 2.9% across both limbs, which is similar to the ranges observed in the current study for the more accurate equations.

Four other studies have investigated the accuracy of generic prediction equations when used to estimate leg press 1-RM performance. Knutzen, Brilla, & Caine (1999) investigated the Brzycki, Epley, Lander, Mayhew et al., O'Connor and Wathen prediction equations when used to estimate supine leg press 1-RM performance in 51 older adults (70.7 ± 6.1 years). The authors reported significant correlations ($p < 0.05$) between predicted and actual 1-RM performance for the six equations (0.786 to 0.802) but did not utilize error statistics. However, it appears that all of the equations underpredicted mean actual 1-RM performance based on the mean predicted 1-RM values (range: -8.52 kg or 14.5% of the mean for the O'Connor equation to -4.94 kg or 8.4% of the mean for the Wathen equation). Importantly, these findings suggest that higher error values occurred in the Knutzen et al. (1999) study compared to the current study. Additionally, while all of the equations in the Knutzen et al. (1999) study underestimated actual 1-RM performance, the majority of the equations in the current study overestimated 1-RM performance. Three main factors may explain these differences. Firstly, Knutzen et al. (1999) used older adults (70.7 ± 6.1 years) while the current study used younger adults (33.15 ± 9.88 years). Therefore, it is possible that the older adults had lower endurance while performing RTFs leading to an underprediction of 1-RM performance, while the younger adults in the current study had greater endurance leading to an overprediction of 1-RM performance for some equations. However, it should be noted that all of the subjects in the Knutzen et al. study were resistance trained, while only some of the subjects in the current study were recently involved in weight training and/or sports. In addition, previous studies have suggested that the accuracy of generic 1-RM prediction equations is similar across different age groups (Kemmler et al., 2006; LeSuer et al., 1997; Mayhew, Kerksick et al., 2004). The second factor to consider is that Knutzen et al. (1999) used a supine leg press exercise, while the current study used a seated leg press exercise. It is possible that intrinsic differences between these variations of the leg press exercise resulted in an underprediction of 1-RM performance in the Knutzen et al. (1999) study but an overprediction in the current study. Finally, the leg press was performed bilaterally in the Knutzen et al. (1999) study but unilaterally in the current study.

In another study that examined the leg press, Wood, Maddalozzo, & Harter (2002) reported average error expressed as a percentage of mean 1-RM for seven prediction equations when estimating 1-RM performance for older sedentary adults (n = 48). Over the full range of RTFs, the authors reported error rates for the equations as follows: Brzycki (97%), Epley (16%), Lander (76%), Lombardi (22%), Mayhew et al. (17%), O'Connor (18%) and Wathen (17%). However, when the analysis was performed only on subjects who performed RTFs ≤ 10 (n = 17), the average error for all seven equations reduced to 10%. Although not directly comparable, these findings appear to demonstrate that greater error rates might have occurred in the Wood, Maddalozzo, & Harter (2002) study compared to the current study.

In a more recent study, Reynolds, Gordon, & Robergs (2006) investigated the accuracy of the Abadie, Brzycki, Epley, Lander and O'Connor equations when estimating 1-RM leg press performance. In addition, the authors developed their own leg press specific prediction equations. The authors reported that their equation, and those of Abadie and Epley, had the smallest mean residuals, with only a slight trend for overestimation. In contrast, the authors stated that the Brzycki, Lander, and O'Connor equations all underestimated actual 1-RM performance, while the nonlinear Lombardi and Mayhew et al. equations were less accurate than the linear equations. Unfortunately, the authors did not report specific results for the generic 1-RM prediction equations to support these statements. However, the authors did report the following standard error of measurement values for all of the equations when 5 RTFs were performed: Abadie (13.74 kg), Brzycki (13.56 kg), Epley (14.05 kg), Lander (13.71 kg), Lombardi (14.16 kg), Mayhew et al., (14.35 kg), O'Connor (13.56 kg) and Reynolds et al. (13.23 kg). Based on the mean actual 1-RM value of 264.1 kg, these values appear to represent error rates of approximately 5%, which is similar to the error rates observed in the current study. This similarity is perhaps not surprising considering that the samples used in both studies appear to be comparable with respect to age, gender mix and training status.

Finally, Kemmler, Lauber, Wassermann, & Mayhew (2006) investigated the accuracy of eight prediction equations when estimating leg press 1-RM performance. The authors reported that an equation they developed (KLW equation) accurately predicted 1-RM performance with mean absolute differences between actual 1-RM and predicted 1-RM of 1.5–2.5% and coefficients of variation of ≤ 3.3%. In addition, the authors reported that the O'Connor equation produced comparable results with mean absolute differences between actual 1-RM and predicted 1-RM of 1.6–2.2% (except for the 3-6 RTF range = 6.2%). However, the Brzycki, Epley, Lander, Lombardi, Mayhew et al. and Wathen equations were not accurate when predicting 1-RM performance over the full range of RTFs (range of mean absolute differences between actual 1-RM and predicted 1-RM: 1.8–32.1%). Nonetheless, the predictive accuracy of these equations was generally superior for the 3-5 and 6-10 RTF ranges (mean absolute differences: 1.9-12.2%) compared to the 11-15 and 16-20 RTF ranges (mean absolute differences: 1.8-32.1%). Importantly, these results appear to be similar to those found in the current study which provides further support for the accuracy of the O'Connor equation when predicting seated leg press 1-RM performance. However, it should be noted that although the KLW equation was the most accurate equation in the Kemmler et al. (2006) study, it tended to underpredict 1-RM performance in the current study. Three main factors may explain this difference. Firstly, the leg press exercise was performed bilaterally in the Kemmler et al. (2006) study but unilaterally in the current study. Secondly, all of the subjects in the Kemmler et al. (2006) study were resistance trained, while only seven of 19 subjects in the current study were resistance trained. If resistance training increases muscular endurance, then it is possible that trained individuals may be able to lift greater percentages of 1-RM at the same number of RTFs, compared to untrained individuals. Importantly, of all the generic prediction equations, the KLW equation uses the greatest percentages of 1-RM at the same number of RTFs to estimate 1-RM performance (see Table 2.7). Therefore, the KLW equation might be more accurate for resistance trained individuals (i.e. those who lift greater percentages of 1-RM at the same number of RTFs), than for untrained individuals. Thirdly, it appears that the subjects in the Kemmler et al. (2006) study did not completely lower the weight stack while performing RTFs and therefore avoided the “sticking point” which occurs at the starting position for this exercise. In contrast, the weights were fully lowered in the current study. This difference may have caused the subjects in the current study to perform slightly less RTFs at the same percentage of 1-RM, compared to the subjects in the Kemmler et al. (2006) study. In turn, this might explain why the KLW equation tended to underestimate leg press 1-RM performance in the current study.

The number of subjects with predicted 1-RM values within 5% of their true 1-RM values differed greatly across the prediction equations. In the affected limbs, the Berger (16/19 or 84%) and Adams, Lombardi and O’Connor (15/19 or 79%) equations produced the most subjects with predicted 1-RM values within 5% of their true 1-RM. In the control limbs, the Adams (15/19 or 79%), Berger (15/19 or 79%) and O’Connor (17/19 or 89%) equations produced the most subjects with predicted 1-RM values within 5% of their true 1-RM. Based on these results, it appears that the more accurate prediction equations in the current study produced a relatively high number of subjects within 5% of their actual 1-RM performance when compared to previous investigations (range: 14.3-68% of subjects within various fixed loads of actual 1-RM performance); (Mayhew, Jacques et al., 2004; Mayhew, Kerksick et al., 2004; Mayhew et al., 1999; Mayhew et al., 2002).

In summary, the Brown, Brzycki, Epley, KLW, Lander, Mayhew et al., Poliquin and Wathen prediction methods appeared to be relatively inaccurate when predicting leg press 1-RM performance in both the affected limbs (ranges: bias -3.1 kg to 4.6 kg, total error 3.7 to 4.8%, subjects within 5% of actual 1-RM 7/19 to 12/19) and the control limbs (ranges: bias -2.7 kg to 5.4 kg, total error 3.8 to 5.3%, subjects within 5% of actual 1-RM 10/19 to 14/19). In contrast, the Adams, Berger, Lombardi and O’Connor equations generally appeared to be relatively accurate when predicting leg press 1-RM performance. However, while these more accurate equations produced similar 95% LOA, ICC, typical error and total error values, the Berger and O’Connor equations demonstrated somewhat superior results with respect to bias and the number of subjects within 5% or less of actual 1-RM performance.

5.3.2. Knee OA Subjects

5.3.2.1. Knee Extension for the Knee OA Subjects

Actual knee extension 1-RM values were greater in the control limbs than in the affected limbs for the knee OA group. This difference represented a mean quadriceps deficit of 19.2% for the affected limbs. This value was less than the side-to-side deficits reported by Hurley, et al. (1997), (30%); Hassan, et al. (2001), (35%); and Pap, et al. (2004), (40-45%) for knee OA subjects. However, this is not surprising considering that the WOMAC scores for the subjects in this study suggested they were considerably less disabled than those in the other studies.

High ICCs were observed for all the prediction methods across both limbs (range: 0.95 to 0.99). However, differences were observed in the lower bound confidence intervals. The Adams, Berger, KLW, Lombardi and O'Connor equations produced the lowest values in the affected (range: 0.49 to 0.89) and control (range: 0.35 to 0.79) limbs. In contrast, the Brown, Brzycki, Epley, Lander, Mayhew et al., Poliquin and Wathen prediction methods produced the highest values in the affected (0.95 to 0.96) and control (0.93 to 0.96) limbs. Therefore, the lower bound confidence intervals for the latter prediction methods support their use when estimating knee extension 1-RM performance in individuals with knee OA. Lovelace (2005) also reported relatively high lower bound confidence intervals for the Brzycki, Epley, Lander and Lombardi equations (range: affected limbs 0.910 to 0.961; control limbs 0.917 to 0.972), but not for the Mayhew et al., O'Connor, Poliquin and Wathen prediction methods (range: affected limbs 0.782 to 0.854; control limbs 0.783 to 0.884). This suggests that the accuracy of some of these equations may differ across the knee extension and calf raise exercises.

The random scatter of data observed in the Bland and Altman graphs suggested that the mean and standard deviation of the differences did not change appreciably over the range of loads lifted. This concurs with Lovelace's (2005) findings for eight 1-RM prediction equations. However, the bias values were greater across both limbs for the Adams, Berger, KLW, Lombardi and O'Connor equations (affected -6.0 to -3.4 kg; control -8.5 to -5.1 kg), compared to the Brown, Brzycki, Epley, Lander, Mayhew et al., Poliquin and Wathen prediction methods (affected -1.6 to 0.0 kg; control -3.1 to -1.1 kg). These findings suggest that the former equations tended to underpredict knee extension 1-RM performance. This occurred because these equations generally use greater percentages of 1-RM to estimate 1-RM performance in the 5-10 RTF range (see Table 2.7). Therefore, the lower bias values observed for the Poliquin (-0.2 kg affected, -1.4 kg control) and Wathen (0.0 kg affected, -1.1 kg control) methods appear to support their use for the estimation of knee extension 1-RM performance in individuals with knee OA. However, it should be noted that a single subject was identified as an outlier with mean percentage differences between predicted and actual 1-RM performance of -14.8% and -14.3% in the affected and control limbs, respectively. This considerable underprediction of knee extension 1-RM performance might be explained by the fact that this subject had participated in surf boat training the day before performing the RTF testing. When this subject's data were excluded from the analyses, the level of bias for the more accurate Brown, Brzycki, Epley, Lander, Mayhew et al., Poliquin and Wathen prediction methods ranged from -0.5 to 1.1 kg in the affected limbs and from -1.7 to -0.1 kg in the control limbs. Therefore, the bias values for all of these equations were within 2% of actual 1-RM performance across both limbs. Similarly, Lovelace (2005) reported that the bias values for eight 1-RM prediction equations were within 3% of actual 1-RM performance across both limbs when subjects with plantarflexor unit injuries performed a calf raise exercise. However, while the Epley, Mayhew et al., Poliquin and Wathen equations produced some of the lowest bias values in the current study, they produced some of the highest values in the Lovelace study (affected limbs: 2.44 to 3.92 kg; control limbs: 3.19 to 4.27 kg). This suggests that the accuracy of these equations differed across the knee extension and calf raise exercises.

The 95% LOA from the Bland and Altman analyses were relatively large for all the prediction methods across both limbs (interval range: 17.0 to 25.7 kg). However, when data from the subject described earlier were excluded from the analyses, the 95% LOA decreased for all of the prediction methods. In the affected limbs, the 95% LOA intervals for the more accurate Brown, Brzycki, Epley, Lander, Mayhew et al., Poliquin and Wathen prediction methods ranged from 9.9 to 11.0 kg. In the control limbs, the 95% LOA intervals for these prediction methods ranged from 10.5 to 14.0 kg. Using the Poliquin prediction method as an example, the results of the current study (n = 11 after the removal of the atypical subject's data) suggest that if the affected limb of another individual was tested, there is a 95% probability that their predicted 1-RM would be between 4.5 kg below and 6.3 kg above their actual 1-RM score. Based on the mean actual 1-RM value of 66.5 kg observed in the current study, these values would represent a range extending from a 6.8% underprediction to a 9.5% overprediction of actual 1-RM performance. Importantly, Lovelace (2005) reported that when subjects with plantarflexor unit injuries performed a calf raise exercise, the Lander equation produced the smallest 95% LOA interval for the affected limbs (-7.09 to 7.27 kg). Based on the mean actual calf raise 1-RM value reported for the affected limbs (131.37 kg), this would represent a range extending from a 5.4% underprediction to a 5.5% overprediction. Thus, in percentage terms, the 95% LOA values were slightly higher in the current study for the more accurate equations.

Typical errors ranged from 3.1 to 3.5 kg in the affected limbs and from 3.6 to 4.6 kg in the control limbs. When converted to typical errors as COVs these values ranged from 3.8 to 4.0% in the affected limbs and from 3.4 to 3.8% in the control limbs. These values suggested that relatively low levels of random error occurred across the two testing procedures. In contrast, the total error of measurement values demonstrated more variability. Total errors were greatest for the Adams, Berger, KLW, Lombardi and O'Connor equations in the affected (range: 5.1-7.8%) and control (range: 5.4-8.3%) limbs. In contrast, total errors were lower for the Brown, Brzycki, Epley, Lander, Mayhew et al., Poliquin and Wathen prediction methods in the affected (range: 3.7-4.1%) and control (range: 3.5-4.2%) limbs. These findings suggest that mean actual 1-RM performance differed considerably from mean predicted 1-RM performance for the former equations. However, when the data from the atypical subject described earlier were excluded from the analyses, the level of error decreased for all of the prediction methods. For the more accurate Brown, Brzycki, Epley, Lander, Mayhew et al., Poliquin and Wathen prediction methods, the typical errors as COVs ranged from 2.5 to 2.6% in the affected limbs and from 2.5 to 2.7% in the control limbs, while the total errors ranged from 2.4 to 2.6% in the affected limbs and from 2.4 to 2.9% in the control limbs. Importantly, the range of typical errors as COVs observed in the current study was similar to that reported by Lovelace (2005) for eight 1-RM equations (range: 1.7 to 2.9% across both limbs).

As mentioned in the knee injury section, it appears that only one study has investigated the accuracy of generic prediction equations when used to estimate knee extension 1-RM performance, while three studies have used this exercise to develop 1-RM prediction equations. Wood, Maddalozzo, & Harter (2002) investigated the accuracy of the Brzycki, Epley, Lander, Lombardi, Mayhew et al., O'Connor and Wathen equations and reported that average error expressed as a percentage of mean 1-RM ranged from 17 to 20% when subjects performed RTFs ≤ 10 ($n = 31$). In addition, Braith, Graves, Leggett, & Pollock (1993) developed a pre-training1-RM prediction equation which had a SEE of 9.3 kg (10.6% of the mean 1-RM value) and a post-training 1-RM prediction equation which had a SEE of 9.9 kg (8.9% of the mean 1-RM value). Abadie & Wentworth (2000) also developed a prediction equation for the knee extension exercise which had a SEE of 2.3 kg (6.9% of the mean 1-RM value). Finally, Dohoney, Chromiak, Lemire, Abadie, & Kovacs (2002) developed a 4-6 RTF equation which had a SEE of 11.9 kg (8.4% of the mean 1-RM value) and a 7-10 RTF equation which had a SEE of 13.7 kg (9.7% of the mean 1-RM value).

Although not directly comparable, it appears that higher error rates occurred in the investigations described above when compared to the current study. Four of the five main factors that might explain these differences in error rates are identical to those discussed in the knee injury section and will not be reiterated. However, with respect to the issue of differences in subject characteristics between the studies, the current study used a sample consisting of six males and six females (mean age 57.4 ± 10.0 years; range 36-76 years), of which four males had weight training experience. Importantly, the mean age of the subjects in the current study appears to be similar to that used in the Wood, Maddalozzo, & Harter (2002) study which consisted of 26 males and 23 females (mean age 53.55 ± 3.34 years), although these subjects were all untrained. In contrast, the Abadie & Wentworth (2000) study used a sample of untrained younger females (mean age 22.2 ± 1.2 years), the Dohoney, Chromiak, Lemire, Abadie, & Kovacs (2002) study used a sample of untrained younger males (mean age 23.2 ± 3.2 years) and the Braith, Graves, Leggett, & Pollock (1993) study used a sample consisting of 33 males and 25 females (mean age 25 ± 5 years) who were initially untrained. However, as mentioned previously, it has generally been demonstrated that age and gender differences do not affect the accuracy of 1-RM prediction equations, while some studies have actually suggested that generic equations may be more accurate when used to estimate 1-RM performance in untrained subjects (Knutzen et al., 1999; Mayhew, Kerksick et al., 2004; Reynolds et al., 2006; Whisenant et al., 2003; Wood et al., 2002) (Braith et al., 1993; Hoeger et al., 1987; Hoeger et al., 1990; Pick & Becque, 2000). Therefore, it appears less likely that differences in subject characteristics could explain the lower error rates observed in the current study when compared to previous investigations.

The number of subjects with predicted 1-RM values within 5% of their true 1-RM values differed greatly across the prediction equations. In the affected limbs, the Poliquin and Wathen prediction methods (11/12 or 92%) and the Brown, Epley, Lander and Mayhew et al. equations (10/12 or 83%) produced the greatest number of subjects with predicted 1-RM values within 5% of their true 1-RM. In the control limbs, the Epley, Lander, Poliquin and Wathen prediction methods (11/12 or 92%) produced the greatest number of subjects with predicted 1-RM values within 5% of their true 1-RM. Based on these results, it appears that the more accurate prediction equations in the current study produced a relatively high number of subjects within 5% of their actual 1-RM performance, when compared to previous investigations (range: 14.3-68% of subjects within various fixed loads of actual 1-RM performance) (Mayhew et al., 2004; Mayhew, Kerksick, Lentz, Ware & Mayhew, 2004; Mayhew et al., 1999; Mayhew et al., 2002).

In summary, the Adams, Berger, KLW, Lombardi and O'Connor equations appeared to be relatively inaccurate when predicting knee extension 1-RM performance in both the affected limbs (ranges: lower bound ICCs 0.489 to 0.885, bias -6.0 kg to -3.4 kg, total error 5.1 to 7.8%, subjects within 5% of actual 1-RM 4/12 to 7/12) and the control limbs (ranges: lower bound ICCs 0.351 to 0.787, bias -8.5 kg to -5.1 kg, total error 5.4 to 8.3%, subjects within 5% of actual 1-RM 3/12 to 6/12) of subjects with knee OA. In contrast, the Brown, Brzycki, Epley, Lander, Mayhew et al., Poliquin and Wathen prediction methods were relatively accurate when predicting knee extension 1-RM performance. However, while these prediction methods produced similar 95% LOA, ICC, typical error and total error values, the Poliquin table and Epley, Lander and Wathen equations demonstrated superior results with respect to bias and the number of subjects within 5% or less of actual 1-RM performance.

5.3.2.2. Leg Press for the Knee OA Subjects

Actual leg press 1-RM values were greater in the control limbs than in the affected limbs for the knee OA group. This difference represented a mean quadriceps deficit of 10.1% for the affected limbs.

High ICCs were observed for all the prediction methods across both limbs (range: 0.95 to 0.98). However, differences were observed in the lower bound confidence intervals. The Brown, Brzycki Epley, Lander, Mayhew et al., Poliquin and Wathen prediction methods produced the lowest values in the affected (range: 0.80 to 0.88) and control (range: 0.81 to 0.90) limbs, while the Adams, Berger, KLW, Lombardi and O'Connor equations produced the highest values in the affected (0.92 to 0.95) and control (0.94 to 0.95) limbs. Thus, the lower bound confidence intervals for the Adams, Berger, KLW, Lombardi and O'Connor equations suggested that these equations exhibited high "relative reliability" when used to estimate leg press 1-RM performance in individuals with knee OA. In contrast, Lovelace (2005) reported relatively high lower bound confidence intervals for the Brzycki, Epley, Lander and Lombardi equations (range: affected limbs 0.910 to 0.961; control limbs 0.917 to 0.972), but lower values for the Mayhew et al., O'Connor, Poliquin and Wathen prediction methods (range: affected limbs 0.782 to 0.854; control limbs 0.783 to 0.884). This suggests that the accuracy of some of these equations may differ across the leg press and calf raise exercises.

The random scatter of data observed in the Bland and Altman graphs suggested that the differences between predicted and actual 1-RM performance did not differ appreciably over the range of loads lifted. Lovelace (2005) reported a similar finding for eight prediction equations when subjects with plantarflexor unit injuries performed a calf raise exercise. However, in the current study the bias values were greater across both limbs for the Brown, Brzycki, Epley, Lander, Mayhew et al., Poliquin and Wathen prediction methods (affected 3.8 to 5.3 kg; control 4.1 to 5.8 kg) than for the Adams, Berger, KLW, Lombardi and O'Connor equations (affected -0.4 to 2.7 kg; control -0.6 to 2.4 kg). These findings suggest that the former prediction methods consistently overpredicted leg press 1-RM performance. This difference between the prediction methods occurred because these prediction methods use lower percentages of 1-RM at the same number of RTFs to estimate 1-RM performance in the 5-10 RTF range (see Table 2.7). Importantly, the bias values observed for the Adams (1.0 kg affected, 0.9 kg control), Berger (1.6 kg affected, 1.6 kg control), KLW (affected -0.4 kg, control -0.6 kg) and O'Connor (1.4 kg affected, 1.2 kg control) equations were all within 3% of actual 1-RM performance and therefore support their use for the estimation of leg press 1-RM performance in individuals with knee OA. Lovelace (2005) also reported bias values that were within 3% of actual 1-RM performance for eight 1-RM prediction equations. However, in contrast to the current study, the Lombardi equation (affected 1.31 kg; control 0.82 kg) produced some of the lowest bias values in the Lovelace study, while the O'Connor equation produced some of the highest bias values (affected -3.17 kg; control -3.71 kg). This suggests that the accuracy of these equations differed across the leg press and calf raise exercises.

The 95% LOA from the Bland and Altman analyses were relatively large for all the prediction methods across both limbs. The KLW equation exhibited the smallest intervals for both the affected limbs (-11.4 to 10.6 kg; interval: 22.0 kg) and control limbs (-12.2 to 11.0 kg; interval: 23.2 kg). However, the Adams, Berger, Lombardi and O'Connor equations also produced similar values in the affected and control limbs. Using the O'Connor equation as an example, the results of the current study (n = 18) suggest that if the affected limb of another individual was tested, there is a 95% probability that their predicted 1-RM would be between 10.1 kg below and 12.8 kg above their actual 1-RM scores. Based on the mean actual 1-RM value of 58.7 kg observed in the current study, these values would represent a range extending from an 17.2% underprediction to a 21.8% overprediction of actual 1-RM performance. Lovelace (2005) also reported 95% LOA values for eight prediction equations. In the affected limbs, the Lander equation exhibited the smallest interval (-7.09 to 7.27 kg). Based on the mean actual calf raise 1-RM value reported for the affected limbs (131.37 kg), this would represent a range extending from a 5.4% underprediction to a 5.5% overprediction. Thus, in percentage terms, the 95% LOA values were superior in the Lovelace study.

Typical errors for all of the equations ranged from 4.0 to 5.2 kg in the affected limbs and from 4.2 to 5.3 kg in the control limbs. When converted to typical errors as COVs these values ranged from 5.9 to 6.3% in the affected limbs and from 5.8 to 6.1% in the control limbs. However, the total error of measurement values demonstrated more variability. In the affected limbs, total errors were greater for the Brown, Brzycki, Epley, Lander, Mayhew et al., Poliquin and Wathen prediction methods in the affected (range: 7.0-8.1%) and control (range: 6.9-8.1%) limbs. In contrast, total errors were lower for the Adams, Berger, KLW, Lombardi and O'Connor equations in the affected (range: 5.8-6.2%) and control (range: 5.7-6.0%) limbs. These findings suggested that although within subject variation was similar across all of the prediction methods, the mean values for actual and predicted 1-RM performance differed more for some equations, with the former prediction methods tending to overpredict knee extension 1-RM performance. Therefore, combined with their low bias values, the lower total error values observed for the Adams (affected 5.8%, control 5.7%), Berger (affected 5.9%; control 5.8%), KLW (affected 5.9%, control 5.9%) and O'Connor (affected 5.8%; control 5.7%) equations suggested that they were the most accurate methods of estimating knee extension 1-RM performance in individuals with knee OA. Lovelace (2005) also reported typical errors as COVs for eight 1-RM prediction methods. These values ranged from 1.7 to 2.9% across both limbs, which was superior to the ranges observed in the current study.

It should be noted that the error rates reported above were the highest observed in this study. A potential explanation for this finding is that a number of knee OA subjects complained of transient crepitus and/or mild discomfort when performing the both the RTF and 1-RM tests for the leg press exercise. It is possible that these factors may have consciously and/or reflexively inhibited muscle performance and therefore contributed to a reduction in accuracy when estimating 1-RM performance. In addition, it is evident from the Bland and Altman graphs that 1-RM performance was appreciably overpredicted for two subjects across all of the equations. Importantly, both of these subjects were involved in weight training and might have possessed greater endurance while performing the RTFs, compared to the other subjects. However, another subject with a similar training background produced quite accurate predicted 1-RM values, while two other subjects with weight training experience produced predicted 1-RM values that often underpredicted actual 1-RM performance.

As mentioned previously, four other studies have investigated the accuracy of generic prediction equations when used to estimate leg press 1-RM performance. Knutzen et al. (1999) reported that the Brzycki, Epley, Lander, Mayhew et al., O'Connor and Wathen prediction equations all underpredicted mean actual 1-RM performance (range: -8.52 kg or 14.5% of the mean for the O'Connor equation to -4.94 kg or 8.4% of the mean for the Wathen equation). These findings differed considerably from the current study. Firstly, while the equations in the Knutzen et al. (1999) study underpredicted 1-RM performance, all but one of the equations in the current study (KLW equation) overestimated mean actual 1-RM performance. Secondly, while Knutzen et al. (1999) found the O'Connor equation provided some of the least accurate estimates of leg press 1-RM performance, it was one of the most accurate equations in the current study. Finally, it appears that slightly higher error levels were reported by Knutzen et al. (1999) compared to the current study. The main factors that might explain these differences were discussed in section 5.3.1.2. Firstly, the subjects in the Knutzen et al. (1999) study were older (70.7 ± 6.1 years) and might have had lower endurance while performing RTFs, leading to the underprediction of 1-RM performance. In contrast, the subjects in the current study were younger (57.44 ± 9.95 years) and might have possessed greater endurance, leading to an overprediction of 1-RM performance. However, some issues undermine this argument. For example, all of the subjects in the Knutzen et al. (1999) study were resistance trained which should theoretically have increased their muscular endurance. In addition, previous studies have generally demonstrated that the accuracy of generic 1-RM prediction equations is similar across different age groups (Kemmler et al., 2006; LeSuer et al., 1997; Mayhew, Kerksick et al., 2004). The second factor that might explain the divergent findings across the Knutzen et al. (1999) study and the current study is intrinsic differences between the leg press exercises that were investigated (supine leg press in the Knutzen et al. study and seated leg press in the current study). Finally, the leg press exercise was performed bilaterally in the Knutzen et al. (1999) study but unilaterally in the current study.

Wood, Maddalozzo, & Harter (2002) also investigated the leg press exercise and reported that for older sedentary adults who performed leg press RTFs ≤ 10 (n = 17), the average error expressed as a percentage of mean 1-RM for seven prediction equations was 10%. Although not directly comparable, these findings appear to demonstrate that slightly greater errors occurred in the Wood, Maddalozzo, & Harter (2002) study, compared to the current study.

In another leg press study, Reynolds, Gordon, & Robergs (2006) reported the following standard error of measurement values for eight prediction equations when 5 RTFs were performed for the leg press exercise: Abadie (13.74 kg), Brzycki (13.56 kg), Epley (14.05 kg), Lander (13.71 kg), Lombardi (14.16 kg), Mayhew et al. (14.35 kg), O'Connor (13.56 kg) and Reynolds et al. (13.23 kg). Based on the mean actual 1-RM value of 264.1 kg, these values appear to represent error rates of approximately 5%. Therefore, although not directly comparable, these results suggest that similar or lower error rates occurred in the Reynolds, Gordon, & Robergs (2006) study than in the current study.

In a more recent study, Kemmler, Lauber, Wassermann, & Mayhew (2006) reported that an equation they developed (KLW equation) accurately predicted leg press 1-RM performance with mean absolute differences between actual 1-RM and predicted 1-RM of 1.5–2.5% and coefficients of variation of ≤ 3.3%. In addition, the authors reported that the O'Connor equation produced comparable results with mean absolute differences between actual 1-RM and predicted 1-RM of 1.6–2.2% (except for the 3-6 RTF range = 6.2%). However, the Brzycki, Epley, Lander, Lombardi, Mayhew et al. and Wathen equations were generally less accurate when predicting 1-RM performance (mean absolute differences of 1.9-12.2% in the 3-5 and 6-10 RTF ranges). Importantly, these findings were similar to those of the current study with respect to the relative accuracy of specific equations, although the error statistics reported by Kemmler et al. (2006) for the more accurate equations appear to be somewhat superior to those found in the current study.

The number of subjects with predicted 1-RM values within 5% of their true 1-RM values differed greatly across the prediction equations. In the affected limbs, the Adams (12/18 or 67%), Berger (12/18 or 67%) and O'Connor (11/18 or 61%) equations produced the greatest number of subjects with predicted 1-RM values within 5% of their true 1-RM. In the control limbs, the Adams (12/18 or 67%), Berger (11/18 or 61%) and O'Connor (11/18 or 61%) equations produced the greatest number of subjects with predicted 1-RM values within 5% of their true 1-RM. In contrast, the results for the KLW (affected 8/18 or 44%, control 9/18 or 50%) and Lombardi (affected 10/18 or 56%, control 9/18 or 50%) equations were slightly lower. Therefore, these and the previous results appear to support the use of the Adams, Berger and O'Connor equations when estimating leg press 1-RM performance in individuals with knee OA. However, it should be recognized that all of these more accurate prediction equations appear to have produced a similar number of subjects within 5% of their actual 1-RM performance, when compared to previous investigations (range: 14.3-68% of subjects within various fixed loads of actual 1-RM performance) (Mayhew et al., 2004; Mayhew, Kerksick, Lentz, Ware & Mayhew, 2004; Mayhew et al., 1999; Mayhew et al., 2002).

In summary, the Brown, Brzycki, Epley, Lander, Mayhew et al., Poliquin and Wathen prediction methods appeared to be relatively inaccurate when predicting leg press 1-RM performance in both the affected limbs (ranges: bias 3.8 kg to 5.3 kg, total error 7.0 to 8.1%, subjects within 5% of actual 1-RM 7/18 to 10/18) and the control limbs (ranges: bias 4.1 kg to 5.8 kg, total error 6.9 to 8.1%, subjects within 5% of actual 1-RM 6/18 to 8/18) of subjects with knee OA. In contrast, the Adams, Berger, KLW, Lombardi and O'Connor equations were more accurate when predicting leg press 1-RM performance. However, while these more accurate equations produced similar 95% LOA, ICC, typical error and total error values, the Adams, Berger and O'Connor equations demonstrated somewhat superior results with respect to the number of subjects within 5% or less of actual 1-RM performance.

5.3.3. Comparison of Knee Injury and Knee OA Groups

5.3.3.1. Knee Extension

The Poliquin table and Wathen equation appeared to be the most accurate methods for estimating knee extension 1-RM performance in subjects with knee injuries and in subjects with knee OA. However, the Epley and Lander equations produced similarly low error values for the knee OA subjects. In contrast, the Adams, Berger, KLW, Lombardi and O'Connor equations were relatively inaccurate and consistently underpredicted knee extension 1-RM performance.

The error rates for the Poliquin table and Wathen equation were similar across the injury and OA groups for the knee extension exercise. However, while the 95% LOA were similar in both groups, the lower loads lifted by the knee OA group suggested that, as a percentage of 1-RM, the potential error interval was greater in the knee OA group compared to the knee injury group. Despite this difference, the results of the current study suggested that the predicted 1-RM values produced by the Poliquin table and Wathen equation generally matched actual 1-RM values closely enough to be clinically acceptable when estimating knee extension 1-RM performance in individuals with knee injuries or knee OA.

5.3.3.2. Leg Press

The Berger and O'Connor equations appeared to be the most accurate methods for estimating leg press 1-RM performance in subjects with knee injuries, while the Adams, Berger and O'Connor equations appeared to be the most accurate methods in subjects with knee OA. In contrast, the Brown, Brzycki, Epley, Lander, Mayhew et al., Poliquin and Wathen prediction methods were relatively inaccurate and tended to overpredict leg press 1-RM performance.

The error rates for the Adams, Berger and O'Connor equations were greater in the knee OA group (typical error: 5.8-6.0%; total error 5.7-5.9%) compared to the knee injury group (typical error: 2.9-3.2%; total error 2.9-3.3%). In addition, the Adams, Berger and O'Connor equations produced fewer subjects within 5% of their actual 1-RM performance in the knee OA group (affected 11/18 to 12/18, control 11/18 to 12/18) compared to the knee injury group (affected 15/19 to 16/19, control 15/19 to 17/19). Finally, the Adams, Berger and O'Connor equations produced wider 95% LOA intervals in the knee OA group compared to the knee injury group. In the knee injury group, the 95% LOA values for these equations suggest that they could probably be used to estimate safe training loads based on mean actual leg press 1-RM performance. Conversely, in the knee OA group, the 95% LOA for these equations suggest that they could potentially overestimate training loads to an unsafe level based on mean actual leg press 1-RM performance. A potential explanation for the higher error levels observed in the knee OA group is that some subjects complained of noticeable crepitus and/or mild discomfort when performing the both the RTF and 1-RM tests for the leg press exercise. No such complaints were reported by subjects in the knee injury group. Therefore, these factors may have consciously and/or reflexively inhibited muscle performance in some knee OA subjects and consequently contributed to the diminished accuracy when estimating leg press 1-RM performance.

5.3.4. Comparison of Knee Extension and Leg Press Exercises

It appears that different equations produced the most accurate estimates of knee extension 1-RM performance (Poliquin table and Epley, Lander and Wathen equations) and leg press 1-RM performance (Adams, Berger and O'Connor equations) in subjects with knee injuries and knee OA. Importantly, compared to the Adams, Berger and O'Connor equations, the Epley, Lander, Poliquin and Wathen prediction methods use smaller percentages of 1-RM at the same number of RTFs to estimate 1-RM performance. This suggests that greater percentages of 1-RM were generally lifted for the leg press exercise compared to the knee extension exercise, at the same number of RTFs. Two main factors might explain this difference. Firstly, several muscle groups are utilized for the leg press exercise, while the quadriceps muscle is the primary agonist for the knee extension exercise. Therefore, relative muscle endurance and strength may be greater when performing the leg press exercise compared to the knee extension exercise. The second factor to consider is that the most unfavourable position for force production (the "sticking point") during the leg press exercise occurred at the starting position. Therefore, failure during both RTF and 1-RM testing occurred at this point. However, for many subjects a relatively small decrease in weight from their 1-RM load allowed them to overcome this sticking point and perform a relatively high number of RTFs. As a consequence, this might explain why the prediction equations which utilized greater percentages of 1-RM at the same number of RTFs (e.g. Adams, Berger and O'Connor equations) were more accurate for the leg press exercise. In contrast, the sticking point for the knee extension exercise occurred at terminal knee extension. Therefore, it appeared that a greater reduction in weight from the 1-RM load was required to achieve full knee extension while performing RTFs. In turn, this might explain why the equations which utilized smaller percentages of 1-RM at the same number of RTFs (i.e. Epley, Lander, Poliquin and Wathen prediction methods) were more accurate for the knee extension exercise. Importantly, these findings appear to concur with those of Hoeger, Barette, Hale, & Hopkins (1987) and Hoeger, Hopkins, Barette, & Hale (1990) who found that the number of RTFs performed for the leg press exercise at 40%, 60% and 80% of 1-RM were significantly higher than those performed for the knee extension exercise (see Tables 2.10 and 2.11). Therefore, these findings support the contention that the number of RTFs completed at selected percentages of 1-RM may vary depending on the exercise being performed. Consequently, it appears that no single generic prediction equation can be used to accurately estimate both leg press and knee extension 1-RM performance in subjects with knee injuries and knee OA. In addition, comparisons with the Lovelace (2005) study suggest that the equations which were accurate for the leg press exercise in the current study (Adams, Berger and O'Connor) would probably not be accurate for the calf raise exercise. In contrast, the equations which were accurate for the knee extension exercise in the current study (Epley, Lander, Poliquin and Wathen) might be relatively accurate for the calf raise exercise. Thus, it could be argued that generic prediction equations should not be used to estimate 1-RM performance for an exercise unless the accuracy of those equations has been demonstrated for that exercise.

5.4. PRACTICAL IMPLICATIONS

The primary practical purpose of generic prediction equations is to estimate 1-RM performance when actual 1-RM testing is inappropriate. Importantly, a number of issues appear to be common to all generic prediction equations when deciding whether these techniques could be used to replace actual 1-RM testing. These issues include the ability to identify side-to-side strength deficits, the ability to accurately re-measure 1-RM performance, the efficiency and safety of the tests and the fact that test-retest error can occur even with repeated 1-RM testing.

Regarding the first issue, the paired t-tests demonstrated that predictive accuracy was similar in the affected and control limbs for all of the equations across both groups and both exercises (after the removal of atypical subjects in the knee injury / knee extension group). Therefore, even if these equations under- or over-estimated actual 1-RM performance, the inaccuracies would probably be similar across both limbs and consequently permit the identification of side-to-side strength deficits.

With respect to the second issue, it appears that a primary aim of maximal strength testing is to periodically re-measure 1-RM performance to determine whether changes in strength have occurred during a rehabilitation programme. The results of some studies have suggested that the accuracy of 1-RM prediction equations is similar across trained and untrained subjects (Mayhew, Ball, Arnold et al., 1992; Mayhew, Ball, & Bowen, 1992). In contrast, other studies have refuted this contention (Braith et al., 1993; Hoeger et al., 1987; Hoeger et al., 1990; Pick & Becque, 2000). However, the longitudinal effect of resistance training on the accuracy of prediction equations was not investigated in the current study. Therefore, further research is required before prediction equations can be used with confidence to re-measure 1-RM performance following resistance training.

With regard to the third issue of efficiency, the RTF tests for the prediction methods were consistently quicker to administer (approximately 5 minutes per limb, per exercise) compared to the actual 1-RM test (approximately 15 minutes per limb, per exercise). Therefore, 1-RM prediction methods would appear to be a more efficient alternative to actual 1-RM testing in clinical settings.

Concerning the fourth issue of safety, one subject had minimal complaint of knee pain during the familiarization session but experienced significant knee pain and swelling afterwards, which lasted for approximately a week. However, because both the RTF and actual 1-RM procedures were performed during the familiarization session, it is unclear which of these tests may have caused the symptoms. Additionally, a number of knee OA subjects complained of significant anterior knee pain when attempting warm up weights for the knee extension exercise. Therefore, further knee extension testing was abandoned for these subjects and they suffered no adverse effects. Finally, none of the subjects who completed the full testing protocol experienced any significant change in symptoms following the RTF or actual 1-RM testing, although some knee OA subjects described transient crepitus and/or mild discomfort during the leg press exercise. Therefore, it remains unclear whether RTF testing is inherently safer than1-RM testing.

Finally, it should be recognized that test-retest error occurs even when actual 1-RM performance is measured repeatedly. For example, Phillips, Batterham, Valenzuela, & Burkett (2004) investigated the reliability of bench press and leg press 1-RM testing in 47 older adults following at least three familiarization sessions. Although these subjects were significantly older than those in the current study, the Phillips et al. (2004) study appears to be the only 1-RM reliability investigation that has reported typical errors as COVs. For the bench press, the authors reported typical errors as COVs between the first and second trials of 5.4% (95% CI: 4.0%–8.7%) and 5.2%

(95% CI: 4.3%–7.3%) for males and females, respectively. Between the second and third trials, the authors reported typical errors as COVs of 4.7% (95% CI: 3.5%–7.5%) and 7.3% (95% CI: 6.0%–10.2%) for males and females, respectively. For the leg press, the authors reported typical errors as COVs between the first and second trials of 6.7% (95% CI: 5.1%–10.9%) and 6.3% (95% CI: 5.1%–8.7%) for males and females, respectively. Between the second and third trials, the authors reported typical errors as COVs of 3.4% (95% CI: 2.6%–5.5%) and 5.6% (95% CI: 4.6%–7.8%) for males and females, respectively. In comparison, when the knee injury group performed the knee extension exercise in the current study, the more accurate Poliquin and Wathen prediction methods produced typical errors as COVs that were lower than these values (affected limbs: 3.1%; range in control limbs: 3.8-3.9%). In addition, when the knee OA group performed the knee extension exercise, the more accurate Epley, Lander, Poliquin and Wathen prediction methods also produced typical errors as COVs that were lower than these values (range in affected limbs: 3.8-4.0%; control limbs: 3.6-3.8%). Similarly, when the knee injury group performed the leg press exercise, the more accurate Berger and O'Connor equations produced typical errors as COVs that were lower than these values (range in affected limbs: 2.9-3.2%; control limbs 2.9-3.1%). Finally, when the knee OA group performed the leg press exercise, the more accurate Adams, Berger, and O'Connor equations produced typical errors as COVs that were similar to the values in the Phillips et al. study (range in affected limbs: 5.9-6.0%; control limbs 5.8-5.9%). Therefore, these findings appear to provide further support for the use of the more accurate prediction methods when estimating knee extension and leg press 1-RM performance in individuals with knee injuries and knee OA.

In conclusion, it appears that the more accurate prediction equations in this study could have been used to replace actual 1-RM testing when measuring knee extension strength in the knee injury and knee OA groups and when measuring leg press strength in the knee injury group. In contrast, it is questionable whether prediction equations could have been used instead of actual 1-RM testing to accurately measure leg press strength in the subjects with knee OA.

5.5. LIMITATIONS

The current study used each subject's unaffected limb as a control. However, some studies have suggested that knee injuries and knee OA can result in bilateral voluntary activation deficits. In addition, arthritic joint changes appear to occur along a continuum and it is possible that asymptomatic degenerative changes were present in the control knees of some subjects in the knee OA group. As a consequence, factors such as these may have affected maximal muscle strength in the control knees.

This study was cross sectional in design. Therefore, it remains unclear whether generic 1-RM prediction equations would remain accurate when performed repeatedly during a rehabilitation programme.

Subject anxiety and safety issues dictated that the unaffected limbs be tested first. Therefore, an order effect may have influenced the results of this study.

A seated leg press machine was investigated in the current study. Therefore, the findings related to this exercise might not be directly applicable to other types of leg press equipment (e.g. 45º leg press or supine leg press).

The exercises in this study were performed unilaterally. Therefore, inferences from the findings might not be applicable when these exercises are performed bilaterally.

Ten subjects in the knee OA group complained of crepitus and/or mild knee discomfort while performing the leg press exercise. This may have consciously and/or reflexively inhibited muscle performance and therefore reduced the accuracy of the prediction equations.

Six subjects in the knee OA group were unable to perform the knee extension exercise due to severe anterior knee pain. Therefore, subject numbers in this group were relatively low (n = 12). In addition, the accuracy of the equations may have been significantly different if these subjects could have been tested.

The subjects with knee OA had a mean WOMAC score of 28.12/240. This was appreciably lower that the WOMAC scores reported for individuals with knee OA in a number of other studies. Therefore, the results of the current study may not be directly applicable to more disabled knee OA populations.

The time from injury to strength testing ranged from 6-300 months with a mean interval of 81.0 months (SD 89.4) for the subjects with knee injuries. Therefore, it remains unclear whether prediction equations would be accurate when estimating knee extension and leg press 1-RM performance for individuals with more acute knee injuries (less than six months duration). Similarly, it remains unclear whether RTF or 1-RM testing procedures could be performed safely by individuals with knee injuries of less than six months duration.

The reliability of actual 1-RM testing was not measured in the current study.

6. CHAPTER 6: SUMMARY & CONCLUSIONS

Knee injuries and knee OA are common musculoskeletal pathologies that can lead to significant quadriceps muscle strength deficits. In turn, these pathologies can result in reduced levels of functional and recreational activity. Therefore, reliable and valid methods of measuring maximal strength would appear to be essential for identifying and quantifying muscle weakness in these populations. However, while numerous methods for assessing muscle strength are available, it has been suggested that maximal strength testing may not be appropriate for individuals with musculoskeletal pathologies due to the risk of re-injury. Consequently, it has been argued that using prediction equations to estimate 1-RM performance from submaximal repetitions to failure might be more suitable for these populations. However, to date, no known studies had investigated the accuracy of generic prediction equations when used to estimate 1-RM performance in subjects with knee injuries or knee OA. Therefore, the purpose of the current study was to investigate the accuracy of twelve prediction methods when used to estimate isoinertial knee extension and leg press 1-RM performance in subjects with knee OA or knee injuries.

A total of 38 subjects participated in this study. None of the subjects were undergoing treatment for their knee pathologies at the time of testing. Each subject attended the testing venue on three occasions. At the first visit a familiarization session was carried out. At the second and third visits each subject was randomly assigned to perform either actual or predicted 1-RM testing for both of the exercises. Twelve different prediction methods were used to estimate 1-RM performance from the results. The estimates of 1-RM strength were then compared with actual 1-RM performance to assess the level of conformity between these measures. Error statistics including Bland and Altman analyses, intraclass correlation coefficients, typical error and the total error of measurement were used in the analyses of the results. In addition, paired t-tests were used to determine whether actual 1-RM values were significantly different across the control and affected limbs. Paired t-tests were also performed to ascertain whether there were any significant differences in predictive accuracy for each equation across the control and affected limbs. Finally, the number of subjects with predicted 1-RM values within 5% or less of their actual 1-RM values was determined for each equation.

Twenty subjects with knee injuries completed testing for the knee extension exercise. The results for this group demonstrated that the Brown, Brzycki, Epley, Lander, Mayhew et al., Poliquin and Wathen prediction methods produced lower levels of error than the Adams, Berger, KLW, Lombardi and O'Connor equations. In addition, when two atypical subjects were excluded from the analysis, the error levels for these equations decreased further. Following the removal of these two subjects, no significant differences in predictive accuracy were found for any of the equations across the affected and control limbs ($p > 0.05$). In addition, the typical errors as COVs and the total errors of measurement were low for the more accurate prediction methods, ranging from 2.4-2.8% and from 2.4-3.5%, respectively. Overall, the Poliquin table and Wathen equation appeared to be the most accurate prediction methods for this sample.

Twelve subjects with knee OA performed the knee extension exercise. The results for this group demonstrated that the Brown, Brzycki, Epley, Lander, Mayhew et al., Poliquin and Wathen prediction methods produced lower levels of error than the Adams, Berger, KLW, Lombardi and O'Connor equations. No significant differences in predictive accuracy were found for any of the equations across the affected and control limbs ($p > 0.05$). In addition, when an atypical subject was excluded from the analysis, the error levels for the equations decreased further. Following the removal of this subject, the typical errors as COVs and the total errors of measurement for the more accurate prediction methods ranged from 2.5-2.7% and from 2.4-2.9%, respectively. Overall, the Poliquin table and the Epley, Lander and Wathen equations appeared to be the most accurate prediction methods for this sample.

Nineteen subjects with knee injuries completed testing for the leg press exercise. The results for this group showed that the Adams, Berger, Lombardi and O'Connor equations produced lower levels of error than the Brown, Brzycki, Epley, KLW, Lander, Mayhew et al., Poliquin and Wathen prediction methods. No significant differences in predictive accuracy were found for any of the equations across the affected and control limbs ($p > 0.05$). In addition, the typical errors as COVs and the total errors of measurement for the more accurate prediction methods ranged from 2.8-3.2% and from 2.9-3.3%, respectively. Overall, the Berger and O'Connor equations appeared to be the most accurate prediction methods for this sample.

Eighteen subjects with knee OA performed the leg press exercise. The results for this group showed that the Adams, Berger, KLW, Lombardi and O'Connor equations produced lower levels of error than the Brown, Brzycki, Epley, Lander, Mayhew et al., Poliquin and Wathen prediction methods. No significant differences in predictive accuracy were found for any of the equations across the affected and control limbs ($p > 0.05$). However, the typical errors as COVs and the total errors of measurement for the more accurate prediction methods were relatively high, ranging from 5.8-6.0% and from 5.7-6.2%, respectively. Overall, the Adams, Berger and O'Connor equations appeared to be the most accurate prediction methods for this sample.

In conclusion, this study provides evidence supporting the use of prediction equations when assessing maximal strength for machine weight knee extension and leg press exercises. As these exercises are commonly employed in lower extremity rehabilitation, these findings are valuable to those clinicians involved in the treatment of individuals with knee joint trauma and osteoarthritis.

7. CHAPTER 7: RECOMMENDATIONS

The findings of the current study contribute to the body of knowledge concerning the accuracy of 1-RM prediction equations. However, many questions remain unanswered. Based on the results of this study and the review of the associated literature, four key issues have been identified as areas for future research.

To date, many studies investigating maximal strength tests have only used measures of correlation to establish the test-retest reliability of these procedures. Therefore, the reliability of some strength testing procedures, including 1-RM testing, might need to be re-established using appropriate error statistics.

The results of the current study demonstrated that the accuracy of individual 1-RM prediction equations varied across exercises and across populations with different musculoskeletal pathologies. Therefore, the accuracy of existing prediction equations might need to be investigated for a variety of common exercises and musculoskeletal pathologies before they could be used with confidence in clinical practice.

A potential use for estimates of 1-RM performance would be to measure changes in strength during a rehabilitation programme. Therefore, it would be of interest to determine the test-retest reliability and sensitivity of generic 1-RM prediction equations for a variety of common exercises and musculoskeletal pathologies during a strength training programme. In addition, it appears that safety concerns regarding the use of 1-RM tests in older populations or populations with injuries may be overstated. Therefore, it would also be of interest to determine the test-retest reliability and sensitivity of actual 1-RM testing for a variety of common exercises and musculoskeletal pathologies during a strength training programme.

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9. APPENDICES

APPENDIX 1

Kellgren-Lawrence Radiographic Classification System

Grade	Classification	Description
0	Normal	No features of OA
1	Doubtful	Minimal osteophytes, doubtful significance
2	Minimal	Definite osteophytes with unimpaired joint space
3	Moderate	Moderate diminution of joint space
4	Severe	Joint space greatly impaired with sclerosis of subchondral bone

Kellgren & Lawrence (1957)

APPENDIX 2

Criteria for Classification of Clinical Osteoarthritis (Altman, 1991)

1. Knee pain and crepitus with activity and morning stiffness < 30 minutes and age > 38years
2. Knee pain and crepitus with active motion and morning stiffness > 30 minutes and bony enlargement
3. Knee pain and no crepitus and bony enlargement

APPENDIX 3

Participant Information Sheet

Date Information Sheet Produced:

07/07/2006

Do you need an interpreter?

English	I wish to have an interpreter	Yes	No
Maori	E hiahia ana ahau ki tetahi Kaiwhakamaori / Kaiwhakapakeha korero	Ae	Kao
Samoan	Oute mana'o ia iai se fa'amatala upu	Ioe	Leai
Tongan	Oku ou fiema'u ha fakatonulea	Io	Ikai
Cook Island	Ka inangaro au I tetai tangata uri reo	Ae	Kare
Niuean	Fia manako au ke fakaaoga e taha tagata fakahokohoko kupu	E	Nakai

Project Title

Quadriceps strength prediction equations in individuals with ligamentous injuries, meniscal injuries and/or osteoarthritis of the knee joint.

Invitation

You are invited to take part in a research study that is being undertaken by the Physical Rehabilitation Research Centre at the Auckland University of Technology. This information sheet explains the study to you, and you can then decide whether you would like to be involved.

Participation is entirely voluntary and if you do agree to take part, you are free to withdraw from the study at any time without having to give a reason.

If you do not understand any aspect of the study described below, please ask for clarification. You do not have to decide immediately about participating in the study. However, if all the participants required are selected before your decision is made, you will not be included in the study.

What is the purpose of this research?

People who have knee injuries or knee arthritis often develop weakness in the muscle in the front of their thigh (the quadriceps muscle). Therefore, health professionals need a method to assess quadriceps muscle strength in people with knee pathology. This testing is often performed by having a person lift weights until they reach the maximum load that they can lift for only one repetition. This is called the 1-repetition maximum. However, this type of testing is strenuous and may increase the risk of aggravating an injury or developing muscle soreness if it is not performed carefully.

Several equations exist that predict muscle strength from the number of repetitions performed with a sub-maximal load. The primary purpose of this study is to determine whether these equations are accurate when used with people who have knee injuries/arthritis. If the equations are accurate they may provide a safer and easier alternative for testing muscle strength in people with knee injuries/arthritis.

The secondary purpose of this study is to determine whether an individual's level of quadriceps muscle strength might influence:

1. a return to sporting activity for people with knee injuries

2. a certain level of physical functioning for people with knee arthritis

This research is being performed as part of the requirements for Matthew Colvin to complete a Master of Health Science Degree. The data collected will be published in a thesis to be held at the Auckland University of Technology Library (Akoranga campus). In addition, the data collected from this study will be used to write a paper that will be submitted to a professional journal for possible publication. Finally, the data collected from this study may be used for presentations at professional conferences.

No material that could personally identify you will be used in any reports unless your personal approval is given for the dissemination of results to specific persons (please see the section below titled "How will my privacy be protected?" for more information on privacy issues).

How are people chosen to be asked to be part of this research?

This study will require 25 volunteers with an injury affecting one knee and 25 volunteers with osteoarthritis affecting one knee.

<u>If you have a knee injury you will need to meet the following criteria:</u>

- A ligament tear (anterior cruciate ligament, posterior cruciate ligament and/or medial/lateral collateral ligament) and/or a meniscus tear in one knee only that affected your physical functioning.

- People who underwent surgical repair for these injuries will also be eligible if the surgery was performed more than 3 months ago and if their doctor has allowed them to return to unrestricted activity.

<u>If you have knee osteoarthritis you will need to meet the following criteria:</u>

- Arthritis in one knee only, preferably diagnosed by x-ray. If you have x-rays or x-ray reports showing the severity of your knee arthritis you are asked to bring them to the familiarization session. If you do not have this information it would be greatly appreciated if you could request it from your doctor. If it is not possible to obtain this information you may still be eligible to participate if we can establish a diagnosis of arthritis using a set of clinical signs and symptoms.

<u>Exclusion criteria for all participants:</u>

You will not be able to participate in the study if:

- you have a recent significant history of a disorder, injury or pain affecting your trunk or legs (other than the knee joint) that interferes with your physical functioning

- you are unable to position your knee for the tests

- you have a systemic arthritic condition such as rheumatoid arthritis

- you have undergone a total knee replacement

- you have any medical conditions that would prevent you from applying maximal physical effort such as high blood pressure, stroke or heart disease.

What happens in this research?

The testing procedures will be divided into three sessions: Each session will be separated by a minimum of two and a maximum of seven days to minimize the risk of muscle soreness. When you come to the sessions you will need to wear clothing that is suitable for exercising in and that will allow the researcher to examine your knee (e.g. shorts or pants that will roll up over your knee).

1. <u>A familiarization session (approximately 1 hour)</u>

   During the familiarization session information about your age, gender, height and weight will be collected. In addition, if you have knee arthritis you will complete a questionnaire about your level of physical activity. Conversely if you have a knee injury you will complete a questionnaire regarding your date of injury, type of injury and your previous and current level of sporting and functional activity. You will then perform a warm-up before being familiarized firstly with the predicted 1-repetition maximum testing procedure and then with the actual 1-repetition maximum testing procedure. This will involve using a stationary bike and lifting weights on both a leg extension machine and a leg press machine.

2. <u>A sub-maximal repetitions to failure testing session (approximately 45 min)</u>

   This session will begin with a warm-up. You will then perform the following procedure on the leg extension and leg press machines, one leg at a time.

   Initially you will select a load that you believe you can lift for about 10 repetitions. If you perform 12 repetitions or less the testing will be complete. If you perform 13 repetitions or more you will stop and rest for 3 minutes. The load will then be increased and the test repeated. If required, this process will continue until a load is reached that restricts you to 12 repetitions or less.

3. <u>A 1-repetition maximum testing session (approximately 45 min)</u>

   This session will begin with a warm-up. You will then perform the following procedure on the leg extension and leg press machines, one leg at a time.

   From the familiarization session we will have an idea of how much weight you can lift. Initially you will attempt a lift using 90% of this weight. If you complete one or more repetitions you will stop and rest for three minutes. The load will then be increased and the test will be repeated. This process will continue until the maximum load that you can lift with proper technique for only one repetition is reached.

What are the discomforts and risks?

The main risks are related to the strength testing procedures.

- There is the risk of delayed onset muscle soreness. As the name suggests this is soreness of the muscles that begins one or more days after exercise. This can occur after lifting heavy weights or doing exercises you are not used to. While this can be uncomfortable the symptoms usually go away after one or two days.
- There is a minor risk of exacerbating of your existing knee injury or knee arthritis.
- There is a minor chance of developing a new injury.

While performing the tests with a sub-maximal load, these risks would be no greater than going to a gym to do weight training exercises on similar equipment. However, during the 1-repetition maximum testing the risks may be slightly greater because you will by trying to lift as much weight as possible.

How will these discomforts and risks be alleviated?

The testing sessions will be separated by a minimum of two days to decrease the risk of delayed onset muscle soreness.

Your pain level prior to, during and after testing will be monitored and testing will be stopped if it appears harmful to you.

You will participate in a session to be familiarized with the equipment and the procedures and you will perform a standardized warm-up at the beginning of each session to minimize the risk of injury.

The researchers involved in the study will be available to you after completion of the study to discuss your situation should any stress, harm or related concerns arise. The researcher who will be conducting the testing sessions (Matthew Colvin) is a registered physiotherapist with post-graduate training in musculoskeletal physiotherapy and is capable of assessing injuries, providing first aid and suggesting appropriate options for further assessment and treatment.

What are the benefits?

A potential benefit to participants is that the testing procedures might reveal existing quadriceps muscle weakness and consequently give you an opportunity to address these deficits in collaboration with your normal healthcare provider. In addition, this research may benefit the wider healthcare community by determining whether specific strength prediction equations can accurately estimate 1-RM performance in people with knee injuries or osteoarthritis. If the equations are accurate they may provide a safer and easier alternative for testing muscle strength in people with knee injuries/arthritis and allow health professionals to use them with more confidence.

What compensation is available for injury or negligence?

In the unlikely event that you experience an injury as a result of your participation in this study you may be covered through the Accident Compensation Corporation (ACC) within its normal limitations. ACC coverage is not automatic and your case would need to be assessed by ACC. If you have any questions about ACC, please contact your nearest ACC office or the researcher.

How will my privacy be protected?

No material that could personally identify you will be used in any reports on this study unless your personal approval is given for the dissemination of results to specific persons. All participants will be assigned a number and only the principal researchers of this study will have access to your name. All participant records will be kept in locked storage area by the principal researchers.

If you wish to have access to the results of this research, you are entitled to request a copy from Peter McNair. These copies will be available after the study is completed and published. After the completion of this study, the data collected will be stored permanently at AUT as part of a secure database about prediction equations. Access to the data will be controlled by Professor Peter McNair.

What are the costs of participating in this research?

The total time required will be approximately 2 and ½ hours spread over the three sessions. For your time you will receive a $30 petrol voucher on completion of the three sessions.

What opportunity do I have to consider this invitation?

Data collection for this study is scheduled to take place in November/December/January 2006 and it is anticipated that all the participants for the study will need to be selected by this time. However, if all the participants required are selected before your decision is made, you will not be included in the study.

How do I agree to participate in this research?

If you agree to participate in the study, please complete the attached consent form or contact Matthew Colvin or Jane Galle for a consent form or further information (see contact details below).

Will I receive feedback on the results of this research?

If you wish to have a copy of the results of this research, you can request one from the project supervisor, Peter McNair. This copy will be available after the study is completed and published.

What do I do if I have concerns about this research?

Any concerns regarding the nature of this project should be notified in the first instance to the Project Supervisor, Peter McNair, *peter.mcnair@aut.ac.nz,* 921 9999 ext 7143.

Concerns regarding the conduct of the research should be notified to the Executive Secretary, AUTEC, Madeline Banda, *madeline.banda@aut.ac.nz*, 921 9999 ext 8044.

Who do I contact for further information about this research?

Researcher Contact Details:

Matthew Colvin at 027-4100-579 or matcol97@aut.ac.nz
or via Jane Galle at jane.galle@aut.ac.nz, 921 9999 ext 7194.

Project Supervisor Contact Details

Peter McNair, *peter.mcnair@aut.ac.nz,* 921 9999 ext 7143.
Duncan Reid, *duncan.reid@aut.ac.nz*, 921 9999 ext 7806

Approved by the Auckland University of Technology Ethics Committee on the 13th of July 2006

AUTEC Reference number 06/110

APPENDIX 4

MEMORANDUM

To: Peter McNair
From: **Charles Grinter** Ethics Coordinator
Date: 13 July 2006
Subject: Ethics Application Number 06/110 **Quadriceps strength prediction equations in individuals with ligamentous injuries, meniscal injuries and/or osteoarthritis of the knee joint.**

Dear Peter

Thank you for providing written evidence as requested. I am pleased to advise that it satisfies the points raised by the Auckland University of Technology Ethics Committee (AUTEC) at their meeting on 21 June 2006 and, acting for the Executive Secretary of AUTEC, I have approved your ethics application. This delegated approval is made in accordance with section 5.3.2.3 of AUTEC's *Applying for Ethics Approval: Guidelines and Procedures* and is subject to endorsement at AUTEC's meeting on 14 August 2006.

Your ethics application is approved for a period of three years until 13 July 2009.

I advise that as part of the ethics approval process, you are required to submit to AUTEC the following:

- A brief annual progress report indicating compliance with the ethical approval given using form EA2, which is available online through *http://www.aut.ac.nz/research/ethics*, including a request for extension of the approval if the project will not be completed by the above expiry date;
- A brief report on the status of the project using form EA3, which is available online through *http://www.aut.ac.nz/research/ethics*. This report is to be submitted either when the approval expires on 13 July 2009 or on completion of the project, whichever comes sooner;

You are reminded that, as applicant, you are responsible for ensuring that any research undertaken under this approval is carried out within the parameters approved for your application. Any change to the research outside the parameters of this approval must be submitted to AUTEC for approval before that change is implemented.

Please note that AUTEC grants ethical approval only. If you require management approval from an institution or organisation for your research, then you will need to make the arrangements necessary to obtain this.

To enable us to provide you with efficient service, we ask that you use the application number and study title in all written and verbal correspondence with us. Should you have any further enquiries regarding this matter, you are welcome to contact me by email at charles.grinter@aut.ac.nz or by telephone on 921 9999 at extension 8860.

On behalf of the Committee and myself, I wish you success with your research and look forward to reading about it in your reports.

Yours sincerely

Charles Grinter

Ethics Coordinator

On behalf of Madeline Banda, **Executive Secretary, AUTEC**

APPENDIX 5

CONSENT TO PARTICIPATION IN RESEARCH

Title of Project: **Quadriceps strength prediction equations in individuals with ligamentous injuries, meniscal injuries and/or osteoarthritis of the knee joint.**

Project Supervisor: **Professor Peter McNair**
Division of Rehabilitation and Occupational Studies
Auckland University of Technology
Ph: 09 921 9999 ext 7143

Researcher: **Matthew Colvin**
Physiotherapist, Master of Health Science Student
Auckland University of Technology

REQUEST FOR AN INTERPRETER			
English	I wish to have an interpreter	Yes	No
Maori	E hiahia ana ahau ki tetahi Kaiwhakamaori / Kaiwhakapakeha korero	Ae	Kao
Samoan	Oute mana'o ia iai se fa'amatala upu	Ioe	Leai
Tongan	Oku ou fiema'u ha fakatonulea	Io	Ikai
Cook Island	Ka inangaro au I tetai tangata uri reo	Ae	Kare
Niuean	Fia manako au ke fakaaoga e taha tagata fakahokohoko kupu	E	Nakai

- I have read and understood the information provided about this research project (Information Sheet dated 07/07/2006.).
  Yes O No O
- I have had an opportunity to ask questions and to have them answered and I have had time to consider whether to take part. Yes O No O

- I understand that I may withdraw myself or any information that I have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way. Yes O No O
- If I withdraw, I understand that all relevant data, or parts thereof, will be destroyed. Yes O No O
- I understand that testing will be stopped if it appears harmful to me or if I request it. Yes O No O
- I understand the compensation provisions in the event of physical injury as a result of my participation in this study. Yes O No O
- I know who to contact if I experience any problems from participating in this study. Yes O No O
- I agree to take part in this research. Yes O No O
- I wish to receive a copy of the report from the research.
  Yes O No O

Participant signature: ....

Participant name: ……………………………………………………………….

Participant Contact Details:

………………………………………………………………………………………..

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………………………………………………………………………………………..

Date:

Approved by the Auckland University of Technology Ethics Committee on the 13th of July 2006 AUTEC Reference number 06/110

Note: The Participant should retain a copy of this form.

APPENDIX 6

Quadriceps Strength Prediction Equations in Individuals with Ligamentous Injuries, Meniscal Injuries and/or Osteoarthritis of the Knee Joint

Questionnaire for Subjects with Ligamentous and/or Meniscal Injuries of the Knee Joint

Type of injury (please note, more than one may apply):

Medial Meniscus O Lateral Meniscus O

Anterior Cruciate Ligament O Posterior Cruciate Ligament O

Medial Collateral Ligament O Lateral Collateral Ligament O

Have you had surgery? Yes O No O Date of Surgery ________________

Which knee was injured? Left O Right O

APPENDIX 7

Quadriceps Strength Prediction Equations in Individuals with Ligamentous Injuries, Meniscal Injuries and/or Osteoarthritis of the Knee Joint

Name:	

<u>This section to be completed by the researcher.</u>

Which knee is affected by arthritis? Left O Right O

Approximately how long ago were diagnosed with arthritis in your knee?
___ months ___ years

Kellgren-Lawrence Grading System for OA:

O Grade 0: No features

O Grade 1: Doubtful: minute osteophyte, doubtful significance

O Grade 2: Minimal: definite osteophyte, unimpaired joint space

O Grade 3: Moderate: moderate diminution of joint space

O Grade 4: Severe: joint space greatly impaired, with sclerosis of subchondral bone

Altman Criteria to Establish the Presence of Knee Arthritis:

O Knee pain and crepitus with activity and morning stiffness< 30 min and age >38 yrs

O Knee pain and crepitus with active motion and morning stiffness > 30 minutes and bony enlargement

O Knee pain and no crepitus and bony enlargement

WOMAC OSTEOARTHRITIS INDEX VERSION VA3.1

Name:	

Instructions to Patients

In Section A, B, and C questions will be asked in the following format. You should give your answers by putting an "***x***" on the horizontal line.

Examples:

1. If you put your "**x**" at the left of the line as shown below, then you are indicating that you have **no** pain.

No Pain |————————————————| Extreme Pain

2. If you put your "**x**" at the right end of the line as shown below, then you are indicating that you pain is **extreme**.

No Pain |————————————————| Extreme Pain

3. Please note:
   a. That the further to the right you place your "***x***" the **more** pain you are experiencing.
   b. That the further to the left you place your "***x***" the **less** pain you are experiencing.
   c. **Please do not** place your **"*x*" past the end of the line.**

You will be asked to indicate on this type of scale the amount off pain, stiffness or disability you have experienced in the last 48 hours.

Complete the questionnaire with respect to you knee.
You should think about your knee when answering the questionnaire. Indicate the severity of your pain, stiffness and physical disability that you feel is caused by arthritis in your knee.

Name:	

Section A
PAIN

Think about the pain you felt in you knee due to your arthritis during the last 48 hours.

(Please mark you answers with an "***x***".)

QUESTION: How much pain do you have?	Study Coordinator Use Only
1. Walking on a flat surface. No Pain ├──────────┤ Extreme Pain	Pain1_______
2. Going up or down stairs. No Pain ├──────────┤ Extreme Pain	Pain2_______
3. At night while in bed. No Pain ├──────────┤ Extreme Pain	Pain3_______
4. Sitting or lying. No Pain ├──────────┤ Extreme Pain	Pain4_______
5. Standing upright. No Pain ├──────────┤ Extreme Pain	Pain5_______

Name:	

Section B
STIFFNESS

Think about the stiffness (not pain) you felt in your knee due to arthritis during the last 48 hours.

Stiffness is a sensation of **restriction** or **slowness** when you move your joints.

(Please mark your answers with an "***x***".)

	Study Coordinator Use Only
6. How **severe** is your stiffness **after first awakening** in the morning? No Stiffness |———————————————| Extreme Stiffness	Stiff6_______
7. How severe is your stiffness after sitting, lying or resting **later in the day**? No Stiffness |———————————————| Extreme Stiffness	Stiff7_______

Name:	

Section C

DIFFICULTY PERFORMING DAILY ACTIVITIES

Think about the difficulty you had in doing the following daily physical activities due to arthritis in your knee during the last 48 hours. By this we mean **your ability to move around and to look after yourself.** (Please mark your answers with an "***x***".)

QUESTION: **What degree of difficulty do you have?**	Study Coordinator Use Only
8. Descending stairs. No Difficulty |————————————————| Extreme Difficulty	PFTN8_______
9. Ascending stairs. No Difficulty |————————————————| Extreme Difficulty	PFTN9_______
10. Rising from sitting. No Difficulty |————————————————| Extreme Difficulty	PFTN10______
11. Standing. No Difficulty |————————————————| Extreme Difficulty	PFTN11______
12. Bending to the floor. No Difficulty |————————————————| Extreme Difficulty	PFTN12______
13. Walking on a flat surface. No Difficulty |————————————————| Extreme Difficulty	PFTN13______

Name:	

DIFFICULTY PERFORMING DAILY ACTIVITIES

Think about the difficulty you had in doing the following daily physical activities due to arthritis in your knee during <u>the last 48 hours</u>. By this we mean **your ability to move around and to look after yourself.** (Please mark your answers with an "***x***".)

QUESTION: **What degree of difficulty do you have?**	Study Coordinator Use Only
14. Getting in or out of a car, or getting on or off a bus. No Difficulty |————————————————| Extreme Difficulty	PFTN14_____
15. Going shopping. No Difficulty |————————————————| Extreme Difficulty	PFTN15_____
16. Putting on your socks or stockings. No Difficulty |————————————————| Extreme Difficulty	PFTN16_____
17. Rising from bed. No Difficulty |————————————————| Extreme Difficulty	PFTN17_____
18. Taking off your socks or stockings. No Difficulty |————————————————| Extreme Difficulty	PFTN18_____
19. Lying in bed. No Difficulty |————————————————| Extreme Difficulty	PFTN19_____

Name:	

DIFFICULTY PERFORMING DAILY ACTIVITIES

Think about the difficulty you had in doing the following daily physical activities due to arthritis in your knee during the last 48 hours. By this we mean **your ability to move around and to look after yourself.** (Please mark your answers with an "***x***".)

QUESTION: **What degree of difficulty do you have?**	Study Coordinator Use Only
20. Getting in or out of the bath. No Difficulty ├────────┤ Extreme Difficulty	PFTN20______
21. Sitting. No Difficulty ├────────┤ Extreme Difficulty	PTFN21______
22. Getting on or off the toilet. No Difficulty ├────────┤ Extreme Difficulty	PTFN22______
23. Performing heavy domestic duties. No Difficulty ├────────┤ Extreme Difficulty	PTFN23______
24. Performing light domestic duties. No Difficulty ├────────┤ Extreme Difficulty	PTFN24______