



Declaration

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This Thesis/Dissertation/Research Project entitled: 'Long-Term Outcomes After Primary Anterior Cruciate Ligament Reconstruction when Comparing Three Surgical Techniques' is submitted in partial fulfilment for the requirements for the Unitec degree of Master of Osteopathy.

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Candidate's declaration

I confirm that:

- This Thesis/Dissertation/Research Project represents my own work;
- The contribution of supervisors and others to this work was consistent with the Unitec Regulations and Policies.
- Research for this work has been conducted in accordance with the Unitec Research Ethics Committee Policy and Procedures, and has fulfilled any requirements set for this project by the Unitec Research Ethics Committee.

Research Ethics Committee Approval Number:

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A handwritten signature in black ink, appearing to read 'Franca Bauer'.

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Long-Term Outcomes After Primary Anterior Cruciate Ligament Reconstruction when Comparing Three Surgical Techniques

Franca Bauer

A thesis submitted in partial fulfilment of the requirements for the degree of the Master of
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Abstract

Background: Anterior cruciate ligament (ACL) reconstruction is one of the most frequent orthopaedic surgeries in young, active people. Secondary graft rupture is common and there is insufficient long-term evidence supporting the application of different surgical techniques to reduce its risk. **Objective:** To investigate and compare outcomes of three primary ACL hamstring graft reconstruction surgeries. **Methods:** Retrospective analysis of primary ACL reconstructions undertaken by one surgeon between 2006 and 2012 using three techniques of different graft placements and anchors were compared: (1) Single bundle graft at the site of the antero-medial bundle (SB), (2) a double-bundle graft with proximal and distal endobutton fixation, (EB), and (3) a double-bundle graft attached in a continuous loop with minimal fixation (MF). The primary measure was ACL graft rupture post-operatively. Secondary outcomes included recurrent rotatory instability, return to sport incidence and time-frame, and patient reported outcome measures (PROMs). **Results:** A total of 216 participants were included (51, 77 and 88 in SB, EB and MF, respectively), 145 (67.1%) male, and aged 30.38 ± 11.63 (mean \pm SD). Patient gender between the three groups was significantly different: 37 (72.5%) for SB, 58 (75.3%) for EB and 50 (56.8%) for MF ($p = 0.026$). There were 151 (69.9%) cases of concomitant injuries (meniscal or chondral), with meniscal injuries making up 65.7% of these injuries. The rates of meniscal injuries were significantly different between the three surgical groups (72.5%, 67.5% and 53.4% for SB, EB and MF, respectively ($p = 0.046$)). Graft failure occurred in 17 (7.9%) surgeries and did not differ statistically between the three surgical groups ($p = 0.284$) at 8.4 years (SD \pm 2.2) follow-up. At a follow up of 9 years (IQR = 7 – 10), 79.3% of participants felt stable with pivoting movements, with no significant difference between groups ($p = 0.353$). Levels of pre- and post-injury activity were not significantly different between groups when using Marx and Tegner scores ($p=0.055$, $p=0.481$), with 56.6% of all participants returning to their previous level of sport at median time of 26.00 (IQR = 12.00-42.50) weeks. **Conclusion:** There were no differences in ACL graft rupture rates or patient-perceived stability after more than 8 years follow-up between three primary ACL reconstruction hamstring graft techniques.

MeSH Keywords: Anterior Cruciate Ligament; ACL reconstruction; hamstring tendon; graft failure; rotatory stability

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List of Abbreviations

ACC	Accident compensation corporation
ACL	Anterior cruciate ligament
ALL	Anterolateral ligament
AM	Anteromedial
AP	Anterior-posterior
BMI	Body mass index
BPTB	Bone-patella tendon-bone
DB	Double bundle
HT	Hamstring tendon
LCL	Lateral collateral ligament
MCL	Medical collateral ligament
MRI	Magnetic resonance imaging
NZ	New Zealand
OA	Osteoarthritis
PCL	Posterior cruciate ligament
PL	Posterolateral
PROMs	Patient reported outcome measures
SB	Single bundle

Introduction to the thesis

This thesis has been divided into three distinct sections. Firstly, a review of the past and current literature is included. This is aimed to provide the reader with in-depth information around the topic, as well as a critical appraisal of the current level of research and the gaps within this. Secondly, a manuscript is provided which includes the methodology used within the thesis, as well as presenting an analysis of the results that have been collected.

Additionally, this section provides a discussion on these results to contextualise the information and to indicate possible further directions of research within the field. The last section of this thesis is the appendix, which contains supplementary information to the thesis including a schematic diagram of the three surgical techniques, ethical consent and approval from the Waitemata and Auckland District Health Board, and a relevant section of an in – house questionnaire.

Literature review

The anterior cruciate ligament (ACL) is one of the most commonly injured ligaments during sports participation (Gianotti et al., 2009; Nagelli & Hewett, 2017). To understand why, the anatomy and mechanics of this ligament must first be understood. The ACL works in conjunction with other structures to stabilise the knee throughout dynamic movements (Kapandji, 2011). The main movements that the ACL restricts are anterior translation of the distal femur on the proximal tibia as well as rotational pivoting movements of the knee (Gabriel, Wong, Woo, Yagi, & Debski, 2004; Girgis et al., 1975). Loading is increased on the ACL when flexion is decreased alongside active contraction of the quadriceps muscles as well as valgus, varus and internal rotation external forces. Due to these roles, the ACL is most commonly injured during sporting activities involving pivoting, jumping, and sudden deceleration (Alentorn-Geli et al., 2009).

Although conservative treatment through intensive rehabilitation and muscle conditioning is an option, ACL reconstructive surgery is viewed as the orthodox treatment (Linko, Harilainen, Malmivaara, & Seitsalo, 2005; Kaeding et al., 2011). The reason for this is generally that the population that is injured is young and active, so therefore composed of people who often wish to return to sport as quickly and easily as possible (Leys, Salmon, Waller, Linklater, & Pinczewski, 2012). ACL reconstruction is one of the most frequently

performed orthopaedic surgeries, with 80% of knee ligament surgery performed in New Zealand (NZ) between 2000 and 2005 involving the ACL (Gianotti, Marshall, Hume, & Bunt, 2009; Schreiber, Eck, & Fu, 2010). The aim of ACL reconstructive surgery is restoring stability to the deficient knee and decreasing the risk of both subsequent injury and osteoarthritis within the joint (Kaeding, Pedroza, Reinke, Huston, & Spindler, 2015; Li et al., 2011; Linko et al., 2005; Mariscalco et al., 2013; Yagi et al., 2002).

Although excellent results in terms of restoring functional knee stability following reconstruction have been widely reported, negative outcomes, including failure of the ACL graft, are not uncommon (Nagelli & Hewett, 2017; Schreiber et al., 2010; van Eck, Lesniak, Schreiber, & Fu, 2010). Graft failure following ACL reconstruction surgery is a devastating outcome for both the patient and the surgeon (Wright, Magnussen, Dunn, & Spindler, 2011). Whilst a rupture of the graft is the most obvious indication of ACL reconstruction failure (Wright, Magnussen, Dunn, & Spindler, 2011), other surgical outcome measures include contralateral ACL rupture (Paterno, Rauh, Schmitt, Ford, & Hewett, 2014), graft laxity (Crawford, Waterman, & Lubowitz, 2013), low scores in patient reported outcome measures (PROMs) (Filbay, Ackerman, Russell, & Crossley, 2017), a failure of return to sport (Arderm, Taylor, Feller, & Webster, 2014) and early incidence of the development of osteoarthritis (OA) (Øiestad, Holm, & Risberg, 2018). Factors that increase the risk of ACL graft failure are not yet clearly understood, however previous literature has cited surgery type and graft technique (Sajovic, Stropnik, & Skaza, 2018), young age (Kaeding et al., 2015), high levels of activity (Shelbourne, Gray, & Haro, 2009), gender (Herzberg et al., 2017), concomitant injuries (Balasingam, Sernert, Magnusson, & Kartus, 2017; Feucht et al., 2015), pre – and post – operative rehabilitation approaches (Failla et al., 2016; Nagelli & Hewett, 2017) and surgical timing (Nadarajah, Roach, Ganta, Alaia, & Shah, 2017).

For this reason, extensive research has focussed on the prevention of both primary ACL disruptions and associated instability (Boden, Dean, Feagin Jr. & Garrett, 2000; Alentorn-Geli et al., 2009; Gianotti, Marshall, Hume, & Bunt, 2009, Crawford, Waterman, & Lubowitz, 2013; Sundemo, Sernert, Kartus, Hamrin Senorski, Svantesson, Karlsson & Samuelsson, 2018). Instability can cause secondary ACL injury to graft repairs in the ipsilateral knee and/or disruption to the native contralateral ACL (Crawford et al., 2013; Pinczewski et al., 2007; Sundemo et al., 2018). Despite the large amount of research around ACL reconstructions (Schreiber, Eck, & Fu, 2010; Van Eck, Schkrohowsky, Working,

Irrgang, & Fu, 2012; Kaeding et al., 2015; Sajovic, Stropnik, & Skaza, 2018), the outcomes and their predictors are poorly understood and have been inconsistently reported. Studies vary with regards to quality, patient population, graft choice and outcome measures, which results in heterogeneity within this research field. Most research states whether autografts or allografts and which tendons were used and specifies whether single – bundle or double – bundle techniques were employed within surgery (Pinczewski, Lyman, Salmon, Russell, Roe & Linklater, 2007; Tiamklang, Sumanont, Foocharoen, & Laopaiboon, 2012; Desai, Björnsson, Musahl, Bhandari, Petzold, Fu, Samuelsson, 2014). However, these reports seldom describe fixation techniques. This lack of detail limits the usefulness of these studies for surgeons especially. Many studies do not assess subjective, patient-focused scores, which may result in false lower rates of graft failure (Filbay, Ackerman, Russell, & Crossley, 2017).

Manuscript

The primary aim of this manuscript was to compare outcomes from three different ACL reconstruction surgical techniques. To assess the rate of surgical failure, the incidence of graft rupture was examined. Additionally, secondary outcomes included patient-reported recurrent rotatory instability, return to sport incidence, and PROMs.

The three ACL reconstructions were performed by a single surgeon in a single centre (Dr Matthew Brick MBChB 1987; FRACS (Orth) 2002; Orthosports, New Zealand) between the 15th of February 2006 and the 12th of June 2012.

This study was split into two phases (Phase A and Phase B). Phase A data collection occurred between February 2013 to June 2014 and was performed by Dr Johan Smalberger (JS) MBChB, BSc, PGDipSurgAnat, MHSc. Within Phase A, a total of 209 participants' data was collected. Due to the unavailability of resources to continue data collection, there was a hiatus in the study between June 2014 and September 2017. Phase B data collection occurred between the 29th September 2017 and 24th November 2018 and was performed by Franca Bauer (FB). Within Phase B, a total of 23 participants' data was collected. Additionally, Phase A patients were re-contacted between the 24th July 2018 and 24th November 2018 and to gather the most recent data possible.

The study protocol remained identical between the two phases, with three exceptions to the measurement tools in Phase B.

- Patient reported outcome measures (PROMs) were changed from hard copy to online surveys for ease of participant use and data analysis. These were offered as a paper copy upon participant request.
- The Tegner activity level scale (Tegner & Lysholm, 1985) was added to the PROMs.
- Two questions were also added to the preliminary questions: Have you reinjured the same knee since the ACL reconstruction? If yes, please specify (incl. approximate date and structure injured); and Does your knee feel stable when twisting or pivoting? (yes or no).

Phase A and B data were analysed together. Results were discussed, and conclusions were drawn from both Phase A and B within this thesis.

This manuscript is written with the aim of being published following review in the ‘Journal of Arthroscopy and Related Surgery’, which is the official journal of the Arthroscopy Association of North America. With the aim of consistency within this document and to facilitate its reading, the font and the line spacing from the literature review have been retained in the manuscript. For the same purposes, the referencing has remained as American Psychological Association 6th edition (APA 6th ed.) within the manuscript rather than the American Medical Association referencing style that the journal follows. These differences will be amended prior to the application for publication within the journal. If the reader would like to know more details on this journal and the guide for authors of manuscripts within it, please follow the online webpage link below:

<https://www.journals.elsevier.com/arthroscopy/>

Section I: Literature Review

The anatomy and biomechanics of the knee

The knee is a bi-condylar synovial hinge joint consisting of three articular bones; the femur, tibia and patella (Gilroy, MacPherson, Schuenke, Schulte, & Schumacher, 2016). It is comprised of three joints; the tibiofemoral, patellofemoral and proximal tibiofibular joint (Drake, Vogl, & Mitchell, 2015). The tibiofemoral joint is weightbearing, whilst the patellofemoral joint allows the quadriceps muscles, consisting of rectus femoris, vastus lateralis, vastus intermedialis and vastus medialis (Stone & Stone, 2012), to act as a fulcrum over the knee anteriorly to the tibia without tendon wear (Gilroy et al., 2016). Additionally, it provides a biomechanical advantage by increasing the effort arm of the class 3 lever created by the pull of these quadriceps' muscles on the lower leg when extending the leg (Aglietti & Menchetti, 1995).

The menisci are fibrocartilaginous bands situated between the medial and lateral femoral condyles and tibial plateau (Eleftherios, Hadidi, & Athanasiou, 2012). They are roughly wedge-shaped and semi-lunar. The medial meniscus is “c-shaped” and the lateral meniscus is almost circular (Bryceland, Powell, & Nunn, 2017). The menisci are fully vascularised at birth. At maturity only the peripheral 10-25% of the meniscal tissues are vascularised and innervated (Arnoczky & Warren, 1982). This peripheral region is also known as the “red-red zone”. The remaining avascular, aneural meniscus is known as the “white-white zone” (Eleftherios et al., 2012). The transition zone between these zones is referred to as the “red-white zone”. The healing capacity of the menisci is related to the vascularisation (Arnoczky & Warren, 1982) and therefore the inner layer is more susceptible to permanent injury from trauma or degeneration.

The menisci improve joint congruence by deepening the articular surface of the tibia (Gilroy et al., 2016; Murlimanju, Nair, Pai, Krishnamurthy, & Philip, 2010). The most prominent biomechanical functions are load transmission to a larger surface area and shock absorption during dynamic movements (Drake et al., 2015; McCann, Ingham, Jin, & Fisher, 2009; Walker & Erkiuan, 1975). Other functions include joint stability, lubrication and proprioception (Levy, Torzilli, Gould, & Warren, 1989; Markolf, Bargar, Shoemaker, & Amstutz, 1981).

The ligaments of the knee are passive non-contractile structures that provide support during movements (Shelbourne, Wilckens, Mollabashy, & DeCarlo, 1991). These are divided into extra- and intracapsular ligaments. The extracapsular ligaments consist of the medial collateral ligament (MCL), lateral collateral ligament (LCL), medial patellofemoral (MPFL), anterolateral ligament (ALL), oblique popliteal ligament and the arcuate popliteal ligament. Intracapsular ligaments consist of the anterior and posterior cruciate ligaments (ACL and PCL, respectively) (Gilroy et al., 2016; Drake et al., 2015; Parsons, Gee, Spiekerman, & Cavanagh, 2015). These ligaments work in conjunction with each other and with other non-ligamentous structures to support the knee in all of its natural movements (Kapandji, 2011).

The knee has movement in six degrees of freedom (three rotations and three translations). Rotations are around three principal axes: the tibial shaft axis, the epicondylar axis and the anteroposterior axis, resulting in internal-external rotation, flexion-extension, and varus-valgus rotation, respectively (Woo, Debski, Withrow, & Janaushek, 1999). The translations are proximal-distal, medial-lateral and anterior-posterior, respectively (Woo et al., 1999).

The anatomy and function of the ACL

The ACL is considered to be an intra-articular but extra-synovial ligament (Zantop, Petersen, Sekiya, Musahl, & Fu, 2006; Petersen & Tillmann, 2002; Petersen & Tillmann, 1999; Shelbourne, Wilckens, Mollabashy, & DeCarlo, 1991; Arnoczky, 1982). The ligament arises proximally from the posterior surface of the medial aspect of the lateral femoral condyle in the intercondylar notch (Zantop et al., 2006). It passes anteriorly, medially and distally on an oblique course towards the tibia (Markatos, Kaseta, Lалlos, Korres, & Efstathopoulos, 2013). On the tibia, it inserts between the medial and lateral tibial spines (Shen, Jordan, & Fu, 2007). The tibial insertion site is wider and stronger than the femoral insertion. It is approximately 11mm in width and 17mm in an anterior-posterior direction, making it approximately 120% of the femoral insertion site (Girgis, Marshall, & Monajem, 1975; C. D. Harner et al., 1995, 1999).

The ACL consists of individual fascicles that fan out over a wide flattened area (Siebold et al., 2015). For functional purposes, these fascicles are divided into two bundles; the anteromedial (AM) bundle, which is situated more vertically, and the relatively horizontal posterolateral (PL) bundle (Girgis et al., 1975).

Both bundles are crucial to knee stability and contribute synergistically with varying biomechanical roles (Buoncristiani, Tjoumakaris, Starman, Ferretti, & Fu, 2006). In extension, the PL bundle is taut, while the AM bundle is less so, therefore resisting anterior tibial translation in this position (Ng et al., 2011). In flexion past 30°, the PL bundle is lax, so the AM bundle restrains anterior translational loads of the femur on the tibia, reaching its maximum tension at 60° (Gabriel, Wong, Woo, Yagi, & Debski, 2004; Girgis et al., 1975). Both bundles restrain varus (bowlegged), valgus (knock-kneed) and rotational forces (Buoncristiani et al., 2006; Gabriel et al., 2004).

Prevalence and mechanism of injury to the ACL

ACL injuries are probably the most significant traumatic soft tissue injury, in terms of prevalence and cost of treatment. Gianotti, Marshall, Hume and Bunt (2009) conducted a study examining 238,488 knee ligament injury claims which had been accepted by New Zealand's (NZ) no-fault injury compensation system (regulated by the Accident Compensation Corporation or ACC) between 2000 and 2005. Within this, Gianotti et al. (2009) noted that 80% of surgery performed on ligaments in the knee involved the ACL. Disruption to the ACL occurs when an excessive tensile force is applied to the knee due to non-contact and contact mechanisms (Yu & Garrett, 2007). In NZ, 65% of ACL-related surgeries are due to sports injuries. The remaining 35% of injuries occur at home, in the workplace (particularly commercial and industrial) or from motor vehicle accidents (Gianotti, Marshall, Hume, & Bunt, 2009). Rugby union, netball, football (soccer) and touch rugby are the sports with the highest rates of ACL injuries in NZ (Gianotti et al., 2009). According to Boden, Dean, Feagin Jr. and Garrett's (2000) study, 72% of ACL injuries are from a non-contact mechanism, which, in NZ, predominately occur whilst playing netball, football, basketball and squash (Gianotti et al., 2009). These injuries mostly transpire with pivoting movements, sudden deceleration and landing (Alentorn-Geli et al., 2009).

Several in-vitro and in-vivo studies examined weightbearing and combinations of external forces (Berns, Hull, & Patterson, 1992; Fleming et al., 2001; Markolf et al., 1995). These studies indicated that the major contributor to ACL loading is an anterior shear force at the proximal end of the tibia. This loading is increased as the angle of knee flexion decreases, as well as with a strong quadriceps muscle contraction causing an anterior shear force through

the patella tendon. When valgus, varus and internal rotation are applied at this point, they further increase loading on the ACL (Berns, Hull, & Patterson, 1992; Fleming et al., 2001; Markolf et al., 1995).

Assessment of knee integrity

In suspected ACL injury, a full clinical assessment of the knee is necessary. The assessment starts with a detailed case history, including the mechanism of injury and features such joint swelling, range and quality of movement, tenderness and pain (Calmbach & Hutchens, 2003; Nadarajah, Roach, Ganta, Alaia, & Shah, 2017). A characteristic mechanism of ACL injury is non-contact sudden deceleration or pivoting. It is typical for the patient to describe hearing or feeling a “pop” and experiencing immediate pain and notable swelling. Typically, gait disturbances, particularly avoidance of quadriceps activation, are observable and the patient may feel a decrease in stability (Berchuck, Andriachhi, Bach, & Reider, 1990).

Orthopaedic examinations, including Lachman’s test, the anterior drawer test and the pivot shift test, are commonly used to assess ACL injury (Nadarajah et al., 2017). Lachman’s and the anterior drawer test are similar in terms of assessing pure anterior drawer of the proximal tibia, however they are performed at different degrees of knee flexion. Lachman’s is 15° – 30° flexion (Calmbach & Hutchens, 2003; Makhmalbaf, Moradi, Ganji, & Omid-Kashani, 2013), whilst the anterior drawer test is 90° flexion (Calmbach & Hutchens, 2003).

Lachman’s is the preferred test, with a sensitivity of 78.6 – 86% and a specificity of 91 – 100% (Jain, Amaravati, & Sharma, 2009; Scholten et al., 2003), whilst the sensitivity and specificity for the anterior drawer test are 62% and 88%, respectively (Scholten et al., 2003).

The pivot shift test includes a combination of internal rotation and valgus forces as well as knee flexion. This test is the most sensitive under anaesthesia, with a sensitivity and specificity of 100% (Jain et al., 2009). However, it is difficult to perform on a conscious patient due to hypervigilance. Therefore, the inability to relax throughout these movements causes the sensitivity to decrease to 18 – 75% (Jain et al., 2009; Scholten et al., 2003).

Additionally, the use of a KT-1000 arthrometer can provide an objective measurement of displacement of the proximal tibia when applying an anterior (or posterior) pull force of 89 N (Bach, Warren, Flynn, Kroll, & Wickiewicz, 1990).

Although the ACL is the most frequently injured ligament in the knee, it is often associated with concomitant injuries (Lohmander, Englund, Dahl, & Roos, 2007). These injuries include

trauma to the other knee ligaments, the menisci, articular cartilage and subchondral bone (Calmbach & Hutchens, 2003; Lohmander et al., 2007). It is therefore important to assess these structures in conjunction with the ACL during the initial knee assessment.

Firstly, the PCL should be examined by looking for posterior tibial displacement with the reverse Lachman's test and the KT1000 if it is available (Feltham & Albright, 2001; Huber, Irrgang, Harner, & Lephart, 1997). The medial and lateral collateral ligaments can be assessed through valgus and varus forces through the knee at 30° of flexion, respectively (Brukner & Khan, 2012; Smith & Green, 1995). The MCL is commonly injured concurrently with the ACL and can be indicated if severe bruising into the soft tissue of the leg is observed as the MCL is an extra-articular ligament (Drake et al., 2015; Nadarajah et al., 2017).

The menisci can be examined by compressing the joint and adding internal and external rotation either passively with Apley's compression test or McMurry's test to detect pain, or actively through the Thessaly test (Mirzatooei, Yekta, Bayazidchi, Ershadi, & Afshar, 2010). The Thessaly test has been reported to have a high diagnostic accuracy rate of 96% for lateral meniscus tears and 94% for medial meniscal tears (Karachalios et al., 2005), and a sensitivity and specificity of 90.3% and 97.7%, respectively (Harrison, Abell, & Gibson, 2009). However, Mirzatooei et al. (2010) found that when an ACL tear is present, the specificity of the Thessaly test was drastically reduced, and so should be used with caution (Mirzatooei et al., 2010). Additionally, palpation of the joint-line can aid in meniscal diagnoses (Nadarajah et al., 2017). An injury to the articular cartilage can mimic meniscal injury in these tests, and like the menisci, can cause locking of the knee, as well as crepitus (Bhosale & Richardson, 2008). Due to this, it is difficult to differentiate damage between the two structures without an MRI.

Radiographs are routinely used to assess for associated fractures. (Nadarajah et al., 2017). Magnetic resonance imaging (MRI) is useful to both diagnose both ACL injury and also concomitant bone and soft tissue injuries. The collective clinical information is then used to determine the most appropriate treatment strategy (Ishibashi, Tsuda, Sasaki, & Toh, 2005; Johnson, Urban, Caborn, Vanarthos, & Carlson, 1998).

Even following the above examinations, the extent of concomitant injuries is often unknown until surgery is performed. For this reason, diagnostic arthroscopies are commonly used for diagnosis. The orthopaedic surgeon will decide upon a surgical versus conservative treatment

strategy most suitable for each patient taking into consideration the collective clinical information.

Surgical techniques

ACL reconstructions have evolved over the past three decades, from open surgical techniques to minimally invasive arthroscopies (Lind, Menhert, & Pedersen, 2009). The reconstruction involves harvesting a tendon graft that is then formed into a bundle(s). These are then passed through a tunnel(s) drilled through the femur and tibia and fixed to the bone to replace the ruptured ligament (Tiamklang, Sumanont, Foocharoen, & Laopaiboon, 2012).

Both autografts (grafts collected from the patient) and allografts (grafts collected from a donor) can be used (Busam, Provencher, & Bach, 2008). Autografts are generally preferred over allografts, as there is a lower failure rate, particularly in younger patients (Van Eck, Schkrohowsky, Working, Irrgang, & Fu, 2012). Autografts are also associated with decreased healing time (Muramatsu, Hachiya, & Izawa, 2008) and no risk of disease transmission (Busam et al., 2008). One of the most common sources of autografts are the hamstring tendons (HT), namely the gracilis and semitendinosus (Muneta et al., 2007). The other is a bone-patella tendon-bone (BPTB), which usually consists the middle third of the patella tendon and its bone insertion sites on the patella and tibia (Aune, Holm, Risberg, Jensen, & Steen, 2001; Pinczewski et al., 2007). In their controlled prospective trial with a 10-year follow up period, Pinczewski et al. (2007) found that the HT produced favourable results. This was due to decreased pain in the harvest site, which can prevent kneeling in BPTB grafts, and a lower incidence of mild radiographic osteoarthritis (Pinczewski et al., 2007). Other studies have supported these findings (Handl et al., 2007; Sajovic, Stropnik, & Skaza, 2018), and additionally have noted that HT have a decreased risk of postoperative complications and pain (Aune et al., 2001; Chee et al., 2017; Shaieb, Kan, Chang, Marumoto, & Richardson, 2002).

There were several limitations of Pinczewski et al.'s (2007) study, including patients not being randomised and examiners not being blinded. Additionally, the surgeon performing these surgeries was experienced in BPTB grafts, whilst only beginning to use the HT for reconstructions. Improvements have also subsequently been made to the fixation techniques of the HT in the tibial tunnel. While this would typically be considered a limitation, it may strengthen these particular findings as a surgeon who was more experienced in the BPTB

graft technique still found improved outcomes for HT reconstructions, which has been corroborated by recent studies (Leys, Salmon, Waller, Linklater, & Pinczewski, 2012; Zaffagnini et al., 2011). Additionally, there has been an increase in the use of double-bundle rather than single-bundle techniques since 1993-1994, which is when the participants in Pinczewski et al.'s (2007) study were operated on. However, Busam et al.'s (2008) systematic review of randomised control trials has suggested that graft type is not the primary determinant of ACL reconstruction success, rather that it is more likely related to technical errors. Based on this, perhaps the surgeon should consider their experience in conjunction with the technique that would theoretically suit the patient the most when considering their treatment plan.

Concerning graft composition, either a single bundle (SB) or a double bundle (DB) technique can be employed for an ACL reconstruction. The traditional reconstruction consists of a SB (Schreiber, Eck, & Fu, 2010), which only mimics the AM bundle (Yasuda et al., 2004). Although this technique has produced satisfactory clinical outcomes in general, it has been indicated that it may be suboptimal in terms of its rotational stability as it only restores anterior-posterior (AP) stability (Yagi et al., 2002). Failing to return both AP stability rotational stability may increase osteoarthritis incidence (Tashman, Collon, Anderson, Kolowich, & Anderst, 2004). Additionally, the SB technique has been shown to result in normal International Knee Documentation Committee (IKDC) scores in a relatively modest proportion of patients (61-67%) (Biau, Tournoux, Katsahian, Schranz, & Nizard, 2007). In an attempt to more closely replicate the full anatomy of the ACL, Mott (1983) and Zaricznyj (1987) introduced the concept of DB techniques. The DB techniques include an AM bundle and PL bundle which would travel through two separate tunnels in the tibia and one in the femur. In 1994, Rosenberg and Graf (1994) introduced a DB technique with two tunnels through the femur, yet only one in the tibia. Muneta et al. (1999) then proposed a new DB technique that included two tunnels through both the femur and the tibia. The rationale was to produce a more anatomically accurate reconstruction, whilst also providing the surgeon with the opportunity to set an initial tension of each bundle to cooperate with each other through the knee's full range of motion (Muneta et al., 1999). Furthermore, studies have indicated that an anatomically placed graft undergoes similar forces to a natural ACL, with a non-anatomically placed graft undergoing substantially greater forces (Kato et al., 2009). More recent studies have confirmed the increased knee stability following this anatomic DB reconstruction technique, which has resulted in an increase of the use of this by orthopaedic

surgeons (Desai et al., 2014; Hussein, Van Eck, Cretnik, Dinevski, & Fu, 2012; Schreiber et al., 2010; Siebold, Dehler, & Ellert, 2008).

DB techniques which mimic the anatomical orientations of the AM and PL bundles can vary according to the number fixation points. For example, one technique consists of two hamstring grafts (the AM bundle from the semitendinosus and the PL bundle from the gracilis) and four tunnels drilled in anatomic position. These grafts are attached both proximally on the femur, and distally on the tibia. Another DB technique requires minimal fixation. It consists of a continuous graft consisting of both the semitendinosus and gracilis that is positioned superiorly up the PL tunnel and then looped around and inferiorly down the AM bundle. It is only attached distally on the tibia at a single fixation point. Both the PL and AM tunnels are drilled in anatomic position.

Surgical outcome measures

There are varying degrees of measuring the success or failure of an ACL graft; the main three of which are graft rupture, rotatory instability and KT-1000 arthrometer scores of more than 3mm when compared bilaterally. In addition to these, contralateral ACL rupture, anterior-posterior knee laxity, the rate of return to sport, patient reported outcome measures (PROMs) and the development of osteoarthritis are also indicators of the success or failure of an ACL reconstruction.

Surgical failure - graft rupture

With the increase of ACL reconstructions performed, subsequent graft ruptures and therefore the number of revision surgeries has also increased (Schreiber et al., 2010; van Eck, Lesniak, Schreiber, & Fu, 2010). Of all measures of surgical failure, a graft rupture is considered to be the most devastating to both the patient and the surgeon (Wright, Magnussen, Dunn, & Spindler, 2011). Additionally, revision surgery is often more technically challenging for the surgeon, increasing the importance of graft rupture knowledge to create prevention strategies (Warme et al., 2012). Wright et al. (2011) conducted a systematic review of prospective studies that explored the rate of ACL graft rupture after a minimum duration of five years. In their review, they found that the risk of rupture was 5.8%. A study with 561 participants who had undergone primary ACL reconstruction a minimum of three years prior, carried out by Webster, Feller, Leigh, & Richmond (2014) found a similar graft rupture rate of 4.5%.

A case series study by Bourke, Salmon, Waller, Patterson and Pinczewski (2012) investigated long-term survival of 755 ACL grafts at a minimum of 15 years. They found that 11% of the participants have sustained a graft rupture. This occurred at a mean of 60 months after surgery, the first 24 months of which showed the highest risk, with 44% of graft ruptures occurring within this timeframe. Bourke et al. (2012) reported that overall graft survival was 95%, 93%, 91%, and 89% at 2, 5, 10, and 15 years, respectively.

Research about the causes of graft rupture is heterogeneous with regard to treatment, activity levels, and possible concomitant injuries (Britt E. Øiestad, Engebretsen, Storheim, & Risberg, 2009). Although this suggests that the aetiology of rupture is multifactorial, a traumatic incident is usually the cause (Feller, Webster, Slullitel, & Galan, 2017). It is important to note that for a graft to rupture traumatically, it is usually due to a predisposition of excessive loading on the graft from a technical error made by the surgeon (Feller et al., 2017). As mentioned previously, there is an increased tendency for surgeons to attempt more anatomically correct ACL reconstructions, which has led to the femoral tunnel being drilled from an anteromedial position rather than through the tibial tunnel (Feller et al., 2017). Magnussen et al. (2012) did not observe a change in graft rupture following this procedural change, however Rahr-Wagner, Thillemann, Pedersen and Lind (2013) noted a statistically significant increase of revision rates, with 5.2% and 3.2% graft failure rates for the anteromedial tunnel drilling in comparison to the tibial tunnel drilling, respectively. However, this increase may have been due to surgeon inexperience with a new technique. Additionally, there is a possibility of this more anatomic placement increasing the feeling of stability and normality within the knee within an earlier timeframe, resulting in patients placing an increased load onto the knee earlier, thereby resulting in an increased risk of re-rupturing.

Whether the femoral tunnel is drilled through an anteromedial position or the tibial tunnel, tunnel malposition is common (J. A. Morgan, Dahm, Levy, & Stuart, 2013). General surgical opinion of ideal tunnel position has changed within the past two decades (Feller et al., 2017). Variation between methods and threshold values for categorising the position in literature is an issue (Warne et al., 2012). Additionally, there have been issues with intra-observer and inter-observer reliability when determining tunnel position postoperatively on plain radiographic film (Warne et al., 2012). Despite this, femoral tunnel malposition is the most frequently identified technical issue that results in graft rupture. Several studies reported high

rates of tunnel malposition between 36 – 79% (Garofalo, Djahangiri, & Siegrist, 2006; Trojani et al., 2011; Wright et al., 2010). Additionally, J. A. Morgan et al. (2013) reported that 60% of cases cited a specific “technical cause of failure”, with femoral tunnel malposition accounting for 25.4% of graft ruptures, and when in combination with other technical errors, this increased to 47.6%. The authors stated that the most common tunnel positioning errors were too vertical (35.9%), too anterior (29.9%) or both (26.5%). Furthermore, Wright et al. (2010) determined that 80% of technical failures within their study were caused by femoral tunnel malposition, which, in agreement with Morgan et al. (2013) made this by far the most common reason for failure.

Contralateral ACL rupture

Subsequent ACL injuries on the contralateral knee have been observed to have a higher incidence than primary injuries in healthy individuals. Although there is variation in specific numbers, more recent literature suggests that this prevalence is much higher than originally thought (Paterno, Rauh, Schmitt, Ford, & Hewett, 2014; Pinczewski et al., 2007). Wright et al. (2007) conducted a cohort study observing the risk of tearing the ACL graft and the intact ACL of the contralateral knee during the first two years after surgery. Of the 235 participants, there were 14 ligament disruptions (6%), 7 (3%) of which were ACL graft ruptures of the ipsilateral knee, while the other 7 (3%) were ruptures of the intact ACL of the contralateral knee (Wright et al., 2007). This study’s main strengths were that they collected data from a variety of surgeons using a variety of surgical techniques, which make the results generalisable, as well as their high follow up of 86%. The obvious limitation of this study was the short follow-up period. This initial two year period has the largest exposure return to sports, which is when it is suggested the incidence of re-ruptures and contralateral ruptures is the highest, especially in early return to sport and if the sport is rigorous in pivoting and cutting movements (Nagelli & Hewett, 2017; Paterno, Rauh, Thomas, Hewett, & Schmitt, 2018; Wright et al., 2007, 2011)

A cohort study which was a 10-year comparison of ACL reconstructions with HT and BPTB grafts was conducted by Pinczewski et al. (2007). From 180 participants, at the 10-year mark, there were 20 and 9 contralateral ACL ruptures in the BPTB and HT grafts, respectively. Combined, this was 16% of the entire cohort. Pinczewski et al. (2007) found that the mean time following surgery for contralateral ruptures in the BPTB and HT graft groups was 59 months and 32 months, respectively. This finding contradicts Wright et al.'s (2007)

hypothesis concerning a decrease in re-rupture and contralateral ruptures at longer follow up periods. Pinczewski et al. (2007) also found no significant difference in risk of contralateral ACL rupture in relation to activity-level at two years following surgery, laxity at two years, or gender.

Seven years later, Paterno et al. (2014) published a cohort study containing 78 participants who were deemed ready to return to sports following reconstruction and completing a rehabilitation program with pivoting/cutting movements following a primary ACL reconstruction (mean age, 17.1 +/- 3.1 years). They were compared with 47 healthy controls who were also involved in pivoting/cutting sports but with no history of ACL injury (mean age, 17.2 +/- 2.6 years). There was no significant difference between the two groups with regard to age, height, weight and sports participation. The overall incidence of a subsequent ACL injury in participants with a primary ACL reconstruction was 23 (29.5%), 16 (69.6%) of which were contralateral ACL injuries, while only 7 (30.4%) were ipsilateral graft tears. The incidence of an ACL injury in the control group, four patients (8.5%), was much lower. These results indicated that young athletes who returned to sport within the first 24 months following ACL reconstruction surgery had 6 times the risk of an ACL injury than athletes of the same age with ACL-healthy knees. However, this study also has its limitations: the sample size was small and only included young patients with high activity levels. This limits the generalisability of the findings for a wider population. It also only included a short follow up. It would be useful to have a longer follow-up period to see whether the incidence increases or decreases with time following surgery. This would have allowed the reader to compare the study with Wright et al. (2007), who showed a higher incidence earlier on with Pinczewski et al.'s (2007) findings of ruptures occurring at longer follow up periods. Webster, Feller, Leigh and Richmond's (2014) case control study examined ACL re-injury rates, as the studies previously mentioned but with a three-year follow up. While the incidence of contralateral ACL ruptures was lower, their investigatory findings were in agreement with Paterno et al. (2014). The contralateral graft injuries occurred in 7.5%, with the highest incidence occurring in those under 20 years of age, with odds increasing three-fold compared to patients over 20 years of age. Furthermore, a return to pivoting/cutting sports increased this incidence by a factor of five.

There may be difficulty in confidently determining whether primary ACL surgery increases the risk of injury to the contralateral knee, or whether the individual has other predisposing

factors that increase their risk of rupture. The contralateral ACL may be at higher risk of rupture as a result from additional force being placed on this side compared to the leg with the primary ACL reconstruction due to functional compensatory mechanisms. However, it may be simply that the first ACL rupture uncovers pre-existing risk due to patient or environmental factors, that reappear as the patient returns to their normal activities.

Graft laxity

Residual post-operative ligament laxity of the ACL graft can increase the risk of a graft rupture, as well as have an effect on overall activity level, as it may lead to patient-reported instability (Crawford, Waterman, & Lubowitz, 2013; Kocher, Steadman, Briggs, Sterett, & Hawkins, 2004). This laxity may also lead to dysfunctional loading of the knee, which can increase the risk of long – term osteoarthritis (Baliunas et al., 2002). Additionally, in patients who already have degeneration, ligament laxity is linked to disease progression, and the presence and severity of osteoarthritic symptoms (Håkan Jonsson, Riklund-Åhlström, & Lind, 2004).

Previous literature suggests that rotatory knee laxity has a higher correlation to a feeling of instability and the development of OA than AP laxity (Ayeni, Chahal, Tran, & Sprague, 2012; Håkan Jonsson et al., 2004; Kocher et al., 2004). However, as Sundemo et al. (2018) note, these studies are few in number and only had short to medium follow up periods with a mean of two years. Jonsson et al. (2004) conducted a study examining 63 patients following ACL reconstruction with a follow up period at both two years and five to nine years. No association between AP laxity at two years and the Tegner activity scale and single-legged hop test at five to nine years was found. Additionally, Kocher et al. (2004) performed a clinical study with a minimum of two-year follow up, in which the authors found no association between the KT-1000 arthrometer measurements, Lachman test scores and subjective outcome measures.

In contrast, Sundemo et al. (2018) found a significant association between manual AP laxity and subjective patient reported outcome measures. This contradiction may be partially explained by the longer follow up period of 16 years, as well as a larger cohort of 193 patients. To increase the validity of the study, both patients and examiners were blinded to the two-year follow up results at the long-term follow up. AP laxity was measured by both the KT-1000 arthrometer as well as two manual AP tests (the anterior drawer and Lachman's

tests). However, in this study, the authors found a discrepancy between the manual AP ligament tests and the KT-1000 arthrometer scores. This led to inter- and intra-practitioner reliability being questioned. Despite these limitations, these results indicated the need for further studies to assess whether rotatory or AP instability have an important clinical effect on the long-term function of the knee following ACL reconstruction.

KT-1000 arthrometer

The KT-1000 knee ligament arthrometer quantifies the degree of AP tibial-femoral displacement (Goodwillie, Shah, McHugh, & Nicholas, 2017). It is the most widely used and most reliable arthrometric device in orthopaedics (A. F. Anderson, Snyder, Federspiel, & Lipscomb, 1992), with a high intra and inter-practitioner reliability (van Thiel & Bach, 2010). Although it is faster and easier to test AP laxity through the Lachman test, studies have found the KT-1000 arthrometer to be a more precise and objective test (Arneja & Leith, 2007; Isberg et al., 2006; Wiertsema, van Hooff, Migchelsen, & Steultjens, 2008).

The device has two sensor pads; one in contact with the tibial tuberosity and the other with the patella. The instrument detects the relative motion in millimetres between the two pads as displacement loads are applied (van Thiel & Bach, 2010). An ACL disruption is representative, if at a force of 89 N, there is a difference of 3 mm or more of anterior tibial displacement between the involved and uninvolved knee (A. F. Anderson et al., 1992; H. Jonsson, Karrholm, & Elmqvist, 1993; van Thiel & Bach, 2010). The main critique of the KT-1000 is that it only assesses AP laxity, and does not quantify rotatory stability (van Thiel & Bach, 2010). Additionally, in the event of bilateral ACL damage, a comparison between knees cannot be utilised, which, as mentioned above, is the threshold for diagnosis with a KT-1000 arthrometer.

Although the KT-1000 arthrometer has historically been used to diagnose ACL disruptions, it is also used to determine AP support of the ACL graft (Goodwillie et al., 2017). An acceptable side-to-side comparison of the graft has not been completely established; however, many researchers use a difference of greater than 5 mm to quantify surgical failure (Aglietti, Buzzi, Menchetti, & Giron, 1996; Bach et al., 1990; Tyler, McHugh, Gleim, & Nicholas, 1999). Despite literature using these scores to assess surgical failure, there is a lack of research regarding whether patients with an increase in AP laxity following reconstruction as measured by KT-1000 arthrometer have worse long-term outcomes (Goodwillie et al.,

2017). Thus, more research is required to validate whether greater than 5 mm side-to-side difference in grafts should be the threshold referred to as “surgical failure”.

Patient reported outcomes measures (PROMs)

Outcome measures that are individually selected by studies can lead to two issues. Firstly, heterogeneity in outcome measures across multiple studies hinders effective evidence synthesis (Macefield et al., 2014). Secondly, the risk of outcome reporting bias has the potential to increase, as researchers can selectively report outcomes that attain statistical significance in order to increase the likelihood of publication (Dwan, Gamble, Williamson, & Kirkham, 2013).

To address these issues, PROMs have been developed with the intention of creating a standardised and validated package of outcomes to be adopted by researchers reporting findings within a field. Secondly, they focus on the patients’ own opinions regarding their health, health-related quality of life outcomes, as well as their own views of their symptoms and functional status (Black, 2013; Costal Tirado et al., 2017). PROMs are acquired from patients directly without any interpretation from clinicians, which also reduces the possibility of surgeon bias, as well as helping to deliver a more patient-centred approach (Appleby & Devlin, 2004; Dawson, Doll, Fitzpatrick, Jenkinson, & Carr, 2010). Two broad types of PROMs were described by Black (2013): disease specific, which are tailored to the symptoms and functional impact of a particular condition; and general, which include aspects of self-care and mobility. A singular PROM can consist of several scales and single items. Multiple PROMs can be used in conjunction with each other to ascertain a range of relevant domains within a study (Macefield et al., 2014). To be considered suitable, a PROM must demonstrate its validity, reliability, responsiveness and appropriateness in a relevant population (Macefield et al., 2014). New literature has indicated that data from PROMs correlate strongly with the success of ACL reconstruction and return to sport (Filbay, Ackerman, Russell, & Crossley, 2017). Commonly used PROMs for the assessment of ACL reconstruction include the Knee Injury and Osteoarthritis Outcome Score (KOOS) questionnaire, the International Knee Documentation Committee (IKDC) Subjective Knee Form and the Tegner and Marx activity scales.

The KOOS questionnaire was developed in the 1990s (Roos, Roos, Lohmander, Ekdahl, & Beynnon, 1998) and has been validated in several reviews (Collins et al., 2016; Garratt,

Brealey, & Gillespie, 2004; Rodriguez-Merchan, 2012). KOOS is now widely used for both research and clinical purposes (Alviar, Olver, Brand, Hale, & Khan, 2011; Collins et al., 2016; Garratt et al., 2004; Rodriguez-Merchan, 2012; Roos & Lohmander, 2003). It is intended to be used for a knee injury that may result in post-traumatic osteoarthritis, such as an ACL, meniscal or chondral injury, and evaluates both short and long-term effects of this (Collins et al., 2016; Roos & Lohmander, 2003). It consists of 42 items in five separately scored subscales: pain, other symptoms, function in daily living, function in sport and recreation and knee-related quality of life (Roos & Lohmander, 2003).

The (IKDC) Subjective Knee Form (Allen F. Anderson, 1994) is a patient-reported outcome score that has been subjected to rigorous statistical evaluation and has been acknowledged as valid, reliable and responsive (Greco et al., 2010; Irrgang et al., 2006; Rodriguez-Merchan, 2012). It is a subjective scale that provides patients with a scoring system for the assessment of three categories: overall function during daily activity, knee-specific symptoms, and the level of symptom-free sports activity (Greco et al., 2010). The symptoms subscale focuses on pain, swelling stiffness and feeling of the knee “giving way”. The sports activity evaluates specific functions, for example, squatting, jumping, rising from a chair and going up and down stairs. The function subscale asks patients one question; “How would you rate the function of your knee on a scale of 0 to 10 with 10 being normal, excellent function and 0 being inability to perform any of your usual daily activities which may include sports?” (Allen F. Anderson, Irrgang, Kocher, Mann, & Harrast, 2006). The overall score ranges between 0 – 100, with 100 indicating no limitation in any of its three categories (Agel & Laprade, 2009). Additionally, the IKDC Subjective Knee Form has been indicated to be sensitive to detecting change over time (Irrgang et al., 2006), and gender and age-specific data has been established to facilitate score interpretation (Allen F. Anderson et al., 2006).

The Tegner activity scale (Tegner & Lysholm, 1985) provides a standardised method of scoring work and sports activities, is the most frequently used instrument amongst activity rating scales (Briggs et al., 2009; Briggs, Kocher, Rodkey, & Steadman, 2006; Halasi, Kynsburg, Tállay, & Berkes, 2004) and has been described as the primary method in making activity level quantifiable (Halasi et al., 2004). The scale, originally developed in 1985 for ACL injury follow up (Tegner & Lysholm, 1985), has been evaluated as reliable, valid and responsive for ACL injury (Briggs et al., 2009; Negahban et al., 2011), as well as others such as meniscal lesions (Briggs et al., 2006). It is a short and easily administered patient

questionnaire with a graded list of activities of daily living, work recreation and competitive sports. The patient selects the level of participation with scores from 0 – 10 that best describes their level of activity before their injury and their current level of activity. A score of 0 corresponds to sick leave and/or disability pension due to knee issues, whilst a score of 10 represents participation in national or international elite sports activities. Tegner & Lysholm (1985) reported a limitation of the scale in which a significant decrease in activity, for reasons not related to post-surgical pain or function, can mask the deterioration of functional results. Although a decrease may be caused by a disruption to the ACL, other outside factors are not assessed and therefore cannot be ruled out. However, there have been no further concerns around this in the literature since (Halasi et al., 2004).

The Marx activity scale (Marx, Stump, Jones, Wickiewicz, & Warren, 2001) is a brief patient-reported instrument and is usually used in conjunction with other instruments, particularly the Tegner activity scale (Marx et al., 2001). However, unlike the Tegner activity scale, it does not focus on the participation of work and sports participation, but measures the components that are common in sporting activities, such as the frequency with which the patient runs, cuts, pivots and decelerates (Halasi et al., 2004; Marx et al., 2001). Its score ranges from 0 – 16, with higher scores representing a higher activity level (Marx et al., 2001). This scale is commonly used in surgical research and is considered a useful score when used in conjunction with the Tegner activity scale (Nadarajah et al., 2017).

Return to sport

As a high percentage of ACL disruptions occur during sports participation, a large proportion of the population that undergo reconstruction are athletes. Athletes who have the highest injury rates are those who participate in pivoting sports (Nagelli & Hewett, 2017). These athletes and their teams typically have two primary goals following rupture. The first is to return to their pre-injury level of activity and to their respective sports as quickly as possible. Secondly, prevention re-injury on the ipsilateral or an ACL rupture on the contralateral knee is of high importance. Despite this, Paterno, Rauh, Schmitt, Ford, & Hewett (2014) stated that a young athlete who returns to sport within one year following an ACL rupture is 15 times more likely to experience a second ACL injury compared to a healthy athlete with no medical history of knee injury. Although significantly reduced, this risk is still apparent within two years of returning to sports, with an athlete being approximately six times more

likely to sustained a second ACL injury compared to an athlete with no ACL disruption history (Paterno et al., 2014).

Despite the increased risks of ACL re-rupture on returning to sport within the first year, athletes commonly have a short injury to surgery time, giving them little time for pre-operative rehabilitation. Additionally, after surgery athletes are often put onto an accelerated post-operative rehabilitation program, as described by Shelbourne & Nitz (1992), rather than a more conservative program, such as that initially suggested by Paulos, Noyes, Grood, & Butler (1981). Current trends focus on early weightbearing and the immediate commencement of exercises to restore muscle strength and knee range of motion (Arden, Webster, Taylor, & Feller, 2010). Following this, athletes are typically expected to return to sport between 6 – 12 months (Cascio, Culp, & Cosgarea, 2004; T. Hewett, Myer, Ford, Heidt, & AJ, 2005; Myklebust & Bahr, 2005), although this may be reduced to as early as 4 – 6 months (T. Hewett et al., 2005). Despite these expectations, a systematic review and meta-analysis performed by Arden, Taylor, Feller, & Webster (2014) found that, whilst 80% of patients returned to some sort of physical activity following surgery, 60% of patients returned to their pre-injury level of sport, and only 55% of competitive level athletes returned to competitive sports. Interestingly this percentage was higher than in the authors' previous meta-analysis, where the return to competitive sport was found to be 44% (Arden, Webster, Taylor, & Feller, 2011). Arden, Taylor, Feller, & Webster (2014) acknowledged this disparity and explained that there were five new studies in the 2014 meta-analysis that focussed on elite level athletes, who have a higher return to sport rate than non-elite athletes.

Nagelli & Hewett (2017) reviewed biological and functional considerations of the knee when looking at athletes returning to (or close to) baseline after surgery. Baseline is considered important as this is the point the at which incidence of re-rupture rates upon return to sport would decrease significantly (Nagelli & Hewett, 2017). The authors observed a marked improvement in joint biological health at a two-year time point, including the absence of bone bruises, graft maturation and sensory (neural) restoration of the ACL, as well functional recovery, including biomechanical and neuromuscular control and quadriceps strength. Additionally, a resolution of symptoms was seen at this point. Therefore, Nagelli & Hewett (2017) concluded that homeostasis of the knee will be restored at two years, at which point the risk of subsequent injury when returning to sports is significantly reduced.

Knee osteoarthritis

Osteoarthritis (OA) is a common, age-related and multifactorial condition that is characterised by degeneration of articular cartilage in a synovial joint (Hunter, 2011). It is associated with osteophyte formation, subchondral sclerosis, bone cysts and synovitis (Hunter, 2011; Samuels, Krasnokutsky, & Abramson, 2008). These changes can be asymptomatic. Symptomatic OA is associated with varying degrees of stiffness, pain and a decrease in joint function (Buckwalter & Martin, 2006). OA is caused by a combination of systemic and mechanical factors. Systemic factors include genetic predisposition and metabolic disorders. Mechanical risk factors for OA include muscle weakness, obesity, dysfunctional gait patterns, or previous injuries (such as an ACL disruption). Mechanical abnormalities lead to incorrect dynamic loading of the joint (Astefhen, Deluzio, Caldwell, & Dunbar, 2008; Lohmander et al., 2007).

OA is the most common type of arthritis with the median age of diagnosis being 55 years (Losina et al., 2013). The prevalence of OA in people following ACL disruption of all ages is alarmingly high (Britt Elin Øiestad, Holm, & Risberg, 2018). Britt Elin Øiestad et al. (2018) found OA through simple radiographs in 30% of patients with a mean age of 40 at a 15 year - follow up from ACL reconstruction, although only half of these were symptomatic. Interestingly, while 42% of participants who did not return to pivoting sport had radiographic OA (25% had symptomatic OA), this was reduced to 18.5% (radiographic) and 5.5% (symptomatic) for participants who had returned to pivoting sports (Britt Elin Øiestad et al., 2018). The causative factors between the significantly reduced rate of OA in individuals who had returned to pivoting sports is unknown. However, there is chance that the individuals who returned to pivoting sports had less initial trauma within the knee following injury, or that they had a more technically successful surgery. These factors could increase the likelihood that they felt comfortable with returning to sports, indicating that there may not be a causal relationship between the two, or in other words, that returning to sport may not in itself be protective against the development of OA. The fact that Øiestad et al.'s (2018) study did not collect information on concomitant injuries is an obvious limitation, although it highlights a further need for research within this area.

Surgical intervention has been used to decrease the risk of degeneration in the future, however there is insufficient research around this to prove that there is a significant decrease in risk when following this treatment plan (Lohmander et al., 2007). Neuman et al. (2008)

compared OA prevalence between two groups that had ruptured their ACL, one of whom had surgical intervention, and one of whom had a conservative treatment plan. The authors found that the occurrence of major meniscal injuries was more than double in the surgical group (81.8%) than that of the non-surgical group (36.1%) (Neuman et al., 2008). This finding could mean that surgical intervention itself did not increase OA risk, rather that the participants who had had surgery had more extensive concomitant injuries (particularly to the menisci) than those who did not. Because of this, it is unclear whether surgical intervention increases or decreases the risk for OA. Randomised and well-designed research involving only participants who had extensive meniscal injury and who both did and did not have surgical intervention could provide a better understanding.

Surgical outcome predictors

Predictors of postoperative outcome after ACL reconstruction have been focussed on within this last decade (Sundemo et al., 2018). Determining both modifiable and nonmodifiable predictors of surgical outcome success or failure, are crucial for developing individualised intervention plans. This increase in the individualisation of treatment may improve post-surgical outcome and aid in re-injury prevention (Hashemi et al., 2011; Sundemo et al., 2018). Some factors that may increase the risk of graft rupture (surgical failure) include female gender, family history, greater age, increased level of activity or early return to sports, especially high intensity and pivot sport, concomitant injuries, surgical timing and pre- and post-operative rehabilitation.

Gender

Male patients are typically overrepresented in ACL literature. This may reflect great male participation in recreational and competitive sports (Ott, Ireland, Ballantyne, Willson, & McClay Davis, 2003). However, when looking at activities in which both males and females participate in, with similar rules and equipment, several studies reported that females have a 2-8 times higher risk of ACL disruption than men (Ageberg, Forssblad, Herbertsson, & Roos, 2010; Arendt & Dick, 1995; Herzberg et al., 2017; Hewett, Zazulak, & Myer, 2007) whilst others found no discrepancy between the two (Ferrari, Bach, Bush-Joseph, Wang, & Bojchuk, 2001; Ott et al., 2003; Teitsma, van der Hoeven, Tamminga, & de Bie, 2014). The differences in injury rates between genders has been proposed to be due to neuromuscular control (Hewett, Myer, Ford, Heidt, & AJ, 2005), female sex hormones (Herzberg et al.,

2017), and anatomical and physiological variation in the lower limb (Griffin et al., 2000; Rozzi, Lephart, Gear, & Fu, 1999).

Hewett et al. (2005) described an increased prevalence of deficits in the dynamic neuromuscular control of joint stability in females compared to males. Dynamic neuromuscular control is vital for active (muscular) restraint of movements, so that the stability of the joint is not completely reliant on passive structures, such as the ACL. Conversely when there is inadequate active restraint to control the joint load under high dynamic stress, the passive restraints are placed under these increased loads. Therefore, lack of active restraint is associated with risk of ACL disruption (Beynon & Fleming, 1998). These deficits along the lower extremity kinetic chain may partially cause the differences in ACL primary injury rates between males and females.

The possibility of hormones increasing the risk of ACL disruptions in females was first brought to light when Liu et al. (1996) discovered oestrogen and progesterone target cells in the ACL. Liu et al. (1996) reported these hormone receptors were present within the joint synovium, stromal fibroblasts and within the walls of the vasculature relating to the ACL. This finding started a research trend into this area to see whether these hormones affected the ACL physiology during certain times of the menstrual cycle. Research since then has found that oestradiol, progesterone and relaxin are the predominant hormones within the menstrual cycle that relate to ACL laxity (Herzberg et al., 2017; Timothy E. Hewett et al., 2007). The fluctuations in these hormones at certain points within the menstrual cycle have been hypothesised to increase ligament laxity. This increases the risk of an ACL disruption, with Drago et al. (2011) finding that female athletes with relaxin levels at more than 6.0 pg/mL were four times as likely to experience an ACL tear than their female counterparts with less than 6.0 pg/mL. Herzberg et al. (2017) performed a systematic review and meta-analysis to clarify the effects of the menstrual cycle and contraceptives on the rate of non-contact injuries to the ACL. The authors suggest that ACL laxity and therefore the risk of injury may increase during ovulation, and that to reduce this risk, hormonal contraceptives can be used to suppress the effect of these hormones. This conclusion is different from a previous systematic review on the subject (Timothy E. Hewett et al., 2007), however in the 10 years between the two, the body of evidence increased substantially, with the total number of participants in studies increasing from 382 to 68,758. However, despite this increase in research

participation, most of these studies have a low strength of evidence, and therefore additional higher-quality studies are required to improve confidence in these findings.

Additionally, there are gender-related anatomical variations that influence knee joint biomechanics. Firstly, there are structural differences including an increased Q-angle, excessive tibial torsion, and increased foot pronation in females compared to males, all of which increase the load on the ACL (Griffin et al., 2000). In addition to these anatomical differences, compared to males, females typically have greater joint mobility and musculotendinous flexibility, increasing their ligament laxity (Rozzi, Lephart, Gear, & Fu, 1999). Although hypermobility is genetic, musculotendinous flexibility can be altered through stretching and conditioning (Griffin et al., 2000). Increase in mobility of the joint may equal a decrease in stability when loaded (Kapandji, 2011).

Several studies have shown a disparity between males and females when looking at secondary ACL disruptions with respect to unilateral graft ruptures versus contralateral ACL disruptions (Salmon, Russell, Musgrove, Pinczewski, & Refshauge, 2005; K. Donald Shelbourne, Gray, & Haro, 2009; Wright et al., 2007). Wright et al. (2007) found that 86% of subsequent ACL injuries in male participants were to ACL graft, whilst 71% of subsequent injuries that occurred in women were on the contralateral knee. Salmon et al. (2005) had similar findings, with an overall subsequent injury rate at 8% for males and 4% for females, with the contralateral disruption rate 7% for females, and only 5% for males. Shelbourne, Gray, & Haro (2009) found a similar trend again, with females having a subsequent ACL injury to the contralateral knee of 7.8%, whilst males only had a rate of 3.7%. The main limitations of these findings in all three studies were that the rate of secondary injuries was low; Wright et al. (2007) at 6%; Salmon et al. (2005) at 12%; and K. Donald Shelbourne et al. (2009) at 9.6%. Due to the low incidence of secondary injuries within the study populations, the above statistics have a decreased validity and larger studies are required.

While hormonal and biomechanical differences may explain the increase in overall female ACL disruptions compared to males, they do not explain the increased rate of contralateral injuries compared to unilateral graft disruptions. Dienst et al. (2007) performed an in vivo analysis using MRI and found that females have anatomically smaller ACL's than males. The mean cross section of the mid-substance of the ACL was 45.2 mm in females compared to 68.4 mm for males with the size of the intercondylar notch being directly related to the size of the ACL. In Shelbourne et al.'s (2009) study, all participants, regardless of gender received

the same graft width, which meant that the majority of males received a graft that was smaller than their native ACL, whilst most females received one that was larger. Incidentally, this would mean that the healthy contralateral ACL would be the larger of the two for males and the smaller for the females. What this could indicate is that upon return to sport, the ACL that is smaller (either graft or native on the contralateral knee) will be the one under larger stress, and therefore have a higher risk of disruption, hence females having higher contralateral ACL ruptures whilst males have a higher rate of graft rupture on the contralateral knee.

Family history

The potential for genetic predisposition of ACL injury is largely unstudied, and therefore still highly contentious. Lambert (1984) produced the first case-controlled study that suggested familial history was a risk factor of ACL rupture. Contrary to this, Anderson, Lipscomb, Liudahl, & Addlestone (1987) reported that family members of participants who had received ACL reconstructions did not have an increase in risk of ACL injury themselves. However, since then three studies have supported Lambert's (1984) finding that family history may be a risk factor related to ACL injury; Christopher D. Harner, Paulos, Greenwald, Rosenberg, & Cooley (1994); Flynn et al. (2005); T. E. Hewett et al. (2010).

Harner et al. (1994) reported that 11 of the 31 (35%) participants that had an immediate family history of an ACL disruption also had a personal history of ACL injury, while only 1 of the 23 (4%) participants with no family history had experienced an ACL injury, making the difference between the groups significant. However, the sample size was small, with 31 participants and 23 controls. This meant that the study's results had little external validity and further studies were required to test the authors' conclusion. A later study by Flynn et al. (2005) reported that participants with a personal history of ACL injury were twice as likely to have an immediate relative with a history of ACL injury compared to participants without an ACL injury history.

A study published in 2010 considered multifactorial combinations of risk factors of ACL injury, and whether these had a potential genetic link (Hewett et al., 2010). The authors did this by comparing only one pair of fraternal twin sisters who participated in high-school football (soccer) and basketball. Based on this single pair of twins, Hewett et al. (2010) concluded that a correlation between identified risk factors, such as increased valgus loading and family history was highly probable, however did not have to be genetic. Cultural, social,

financial and environmental factors were highlighted as possible influences of the predisposition of an athlete and their immediate family to ACL disruption. The authors concluded that these factors should be studied before genetic correlation in relation to ACL injury could be better understood. Since this study only examined one set of fraternal twin sisters their results could be purely coincidental. A second limitation was that the authors only examined biomechanical and neuromuscular control during landing, while a large proportion of ACL rupture also occurring during rapid deceleration and pivoting movements.

The above studies indicate that a previous ACL injury in an individual's immediate family may be a risk factor for the individual experiencing an ACL disruption. However, the studies all had relatively small sample sizes and were likely to be statistically underpowered for these multiple regression analyses, which decreases the robustness of their findings. Additionally, four studies suggesting a theory is not significant in a research pool as large as the one around risk factors of ACL ruptures.

Age

Whilst ACL disruptions, and therefore, reconstruction surgery is increasing in prevalence across all ages, recent research has indicated that the most rapid growth has occurred at a younger ages (Dodwell et al., 2014; Mall et al., 2014; Shaw & Finch, 2017; Werner, Yang, Looney, & Gwathmey, 2016). The current plausible explanation for this is the rise in competitive athletic activity that include high-load movements on the ACL among skeletally immature individuals. Additionally, single-sport concentration is increasing, as well as year-round participation in competitive sports (Fabricant et al., 2013; Frank & Gambacorta, 2013; Shea, Grimm, Ewing, & Aoki, 2011). This rise in single-sport concentration and year-round participation suggests that athletes are more likely to perform movements unique to a sport repetitively and without a rest period, putting more stress on specific structures within the knee, such as the ACL. Furthermore, research has indicated that subsequent ACL disruptions following reconstructive surgery are also more common in a younger population (Kaeding et al., 2011; Kaeding et al., 2015; Kamien, Hydrick, Replogle, Go, & Barrett, 2013; Webster, Feller, Kimp, & Whitehead, 2018).

At the time of their publication, Kaeding et al. (2011) produced the first prospective cohort study that demonstrated a younger age as being a major risk factor for ACL graft tear. The mean age in the study was 26.6 years (+/- 10.9), with age being split into six groups (10-19,

20-29, 30-39, 40-49, 50-59, 60-69). The authors found that the group with the highest rate of graft tear was the 10-19-year-old group (36.5%), and across the entire study population, the odds of a participant experiencing a graft rupture was 2.3 times higher in comparison with a participant 10 years their senior (when controlling for graft type). Simply put, when the graft type is constant, when a participant's age is increased by 10 years, there is a 43% reduction in the risk of an ACL graft rupture (Kaeding et al., 2011). Although all of the participants within this study were given the same guidelines for return to sport, this study failed to assess pre-injury level of activity or return to sport times. This additional baseline measurement may have given a more thorough understanding of reasons why younger patients with ACL reconstructions were more likely to experience an ACL graft rupture. Additionally, the study failed to report on contralateral ACL ruptures following primary ACL revision surgery.

A later study which incorporated contralateral ACL rupture risks as well as ipsilateral graft tears was performed by Kaeding et al. (2015). The authors found that the risk of an ipsilateral graft rupture decreased by 9% for every yearly increase in age, while the odds for contralateral ACL tear decreased by 4% for every yearly increase (Kaeding et al., 2015). Recent studies have confirmed that younger patients are at a higher risk of ACL graft failure, reporting rates between 15 – 20% (Kamien et al. 2013; M. D. Morgan, Salmon, Waller, Roe, & Pinczewski, 2016; Webster & Feller, 2016; Webster, Feller, Kimp, & Whitehead, 2018).

Level of activity

Level of activity is associated with both primary and secondary ACL injury rates and strongly associated with age. Shelbourne, Gray, & Haro (2009) performed a cohort study with 1820 participants with a median age of 21 years observing relationships between subsequent ACL injuries and age. Although specific sport exposure rates were not recorded in Shelbourne et al. (2009) study, the authors found that there was a significant difference in activity level between younger (<18 years) and older (18 – 25years, >25 years) groups of participants pre-injury. The type of activity was also important. The study considered sports “high risk” if they involved jumping, twisting or pivoting and included sports such as soccer, American football, volleyball, basketball and skiing.

Within the <18-year-old group, 92% participated in high-risk sports before surgery, whilst 89% of participants between 18 – 25 years and 79% of participants over 25 years did the same. Additionally, following ACL reconstruction, young participants played sports at a

higher intensity than older people, as well as playing sports that had a higher frequency of matches between teams. Overall, 92% of the under 18-year group returned to high-risk sports, whilst only 85% and 68% of participants between 18 – 25 years and over 25 years returned to these sports, respectively. The authors concluded that subsequent ACL injury to either the ipsilateral or contralateral knee was most closely linked to high levels of activity (K. Donald Shelbourne et al., 2009).

Salmon, Russell, Musgrove, Pinczewski, & Refshauge (2005) reported similar findings, with participants who returned to “moderate or strenuous” activities having an 8% incidence of ipsilateral graft rupture and a 10% incidence of contralateral ACL disruption, whilst participants who returned to “light or sedentary” activities only had a 4% and 1% incidence of disruption to the ipsilateral (graft) and contralateral (native) ACL, respectively. A later study by Kaeding, Pedroza, Reinke, Huston, & Spindler (2015) found higher activity levels, as indicated by scores on the Marx activity scale, correlated with both ipsilateral and contralateral secondary ACL injuries.

The increase in the prevalence of primary and secondary ACL failures in younger patients may be linked to their level of activity, i.e. younger patients may be more likely to play vigorous, pivoting sports than older patients, thereby increasing their risk of primary injury (K. Donald Shelbourne et al., 2009). Additionally, competitive younger athletes, compared to older, may participate in an accelerated rehabilitation programme and be more eager or more encouraged to play competitive sport again sooner, increasing their risk of re-injury.

Concomitant injuries

Damage to other structures of the knee in conjunction with the ACL during a traumatic mechanism of injury is common and well recognised (Brophy, Zeltser, Wright, & Flanigan, 2010; Kilcoyne, Dickens, Haniuk, Cameron, & Owens, 2012). These other structures include the meniscal or articular cartilage (Balasingam, Sernert, Magnusson, & Kartus, 2017; Feucht et al., 2015).

The reported incidence of meniscal damage is varied, with percentages ranging between 16% to 82% when the ACL is ruptured through a traumatic incident (Bellabarba, Bush-Joseph, & Bach, 1997; Shoemaker & Markolf, 1986; Warren & Levy, 1983). Kilcoyne et al.'s (2012) prospective study was the first to investigate rates of concomitant meniscal tear during ACL disruption that included a large sample size of over 10,000 military cadets. The authors

reported an incidence of 140 meniscal tears from the 353 participants with ACL injury (39.6%). When comparing medial and lateral menisci, 19.3% and 13.3% has isolated tears, respectively, with 71% participants experiencing a tear to both menisci in the unilateral knee (Kilcoyne et al., 2012). Aside from sample size, other strength of this study was the inclusion of additional patient demographic information. However, although the population was large, it predominately consisted of young males, limiting the generalisability to females and older males.

In their 5 to 15-year prospective follow-up post ACL reconstruction, Shelbourne & Gray (2000) found that articular cartilage damage was the largest predictor of poor long-term subjective and objective results. In their systematic review, Brophy et al. (2010) agreed with these findings, however the authors also highlighted that research around this topic was limited. The authors suggested that further research should be performed focusing on combined ACL reconstruction and cartilage restoration surgery. Additionally, an increase in long-term follow-up studies was required to better understand the relationship between concomitant cartilage damage and OA in conjunction with ACL reconstructions. Balasingam et al.(2017) published a study comparing clinical outcomes, (especially OA through the KOOS scores (Roos et al., 1998)) in patients who had experienced concomitant articular cartilage and meniscal damage alongside their ACL disruption, and patients who had experienced an isolated ACL disruption at a 5- and 10-year follow-up. The authors found that participants with concomitant articular and meniscal damage, experienced a deterioration in the KOOS scores at both the 5- and 10-year follow-up, while the participants with an isolated ACL rupture did not (Balasingam et al., 2017). This indicates that participants with a concomitant injury were more likely to develop OA in the long-term. However, the study did not grade the concomitant injuries, so conclusions drawn from this must be done so at caution, as there is a chance that the participants within this study had a higher rate of high-grade concomitant injuries than is normal.

Surgical timing

Prior to the 1990s, surgical timing was largely unrecognised as an important factor in the post-operative success of an ACL reconstruction. However, in the early 1990's Shelbourne, Wilckens, Mollabashy, & DeCarlo (1991) released a landmark paper suggesting that postponing the surgery until a minimum of three weeks after acute ACL injury would result in an earlier return of strength and reduce the incidence of arthrofibrosis, which would

significantly decrease post-operative stiffness. In the following years, several studies substantiated this proposal (Cosgarea, Sebastianelli, & DeHaven, 1995; C D Harner, Irrgang, Paul, Dearwater, & Fu, 1992; Wasilewski, Covall, & Cohen, 1991). However, the results of these studies are now over 20 years old. Not only has there been an increase in literature around timing since, but there have also been vast improvements in the acute management and surgical techniques around ACL reconstructions (Evans, Shaginaw, & Bartolozzi, 2014). Because of this, the results must be interpreted cautiously, and more recent research must be considered.

Although there is no consensus within the current literature on surgical timing, some trends within research have been reported. Several studies suggest that a shorter time between ACL rupture and reconstruction is favourable (Church & Keating, 2005; Demirag, Aydemir, Danis, & Ermutlu, 2011; Granan, Bahr, Lie, & Engebretsen, 2009). Incentives for a brief injury to surgery delay include limiting muscle atrophy and therefore loss of strength from disuse (particularly the quadriceps), as well as decreasing the risk of injury to further ligamentous, meniscal or chondral structures due to the instability of the injured knee (Duquin et al., 2009; Kwok, Harrison, & Servant, 2013). Justification for delaying surgery for more than three weeks post-injury include; minimising inflammation, improving muscle strength (particularly the quadriceps) through pre-operative rehabilitation, regaining range of motion and allowing surrounding soft tissue to heal from the initial trauma (Mayr, Weig, & Plitz, 2004; Millett, Pennock, Sterett, & Steadman, 2004; Raviraj, Anand, Kodikal, Chandrashekar, & Pai, 2010)

What must also be acknowledged is that, like any other aspect of the health system, long waiting lists are common in surgical practices, and so even if certain studies recommend shorter injury-to-surgery times, this may not be practically viable for regular individuals (Curtis, Russell, Stoelwinder, & Mcneil, 2010). Additionally, to be referred to a surgeon in NZ, an individual must first seek primary health care which may have additional wait-lists (New Zealand Government, 2018; Osteopathic Council New Zealand, n.d.). An exception of this is when considering high-level athletes who frequently receive surgery as soon as possible in order to attempt to return to their sport in the shortest amount of time (Evans et al., 2014).

Mayr et al. (2004) not only studied the effects of timing, but also assessed preoperative knee status, including the irritability of the knee through swelling, redness and heat, following

rupture. The authors reported a correlation between surgery within four weeks of injury and the development of arthrofibrosis. Additionally, the authors reported an association between preoperative irritation and arthrofibrosis. Participants who had reconstructive surgery after four weeks with an irritated knee had a similar chance of developing arthrofibrosis as participants who had surgery earlier with knee irritability. In addition, the authors reported that pre-operative limitations in knee extension and flexion range of movement were also predictive of post-operative arthrofibrosis. These results indicated that the pre-operative status of the knee may be a larger factor in determining ideal surgical timing than simple timing protocols (Mayr et al., 2004). Similarly, the suggestions that surgical timing may need to be reviewed case by case, or whether surgical timing is of any importance are also increasing in popularity (Barber-Westin & Noyes, 2011; Beynnon, Johnson, Abate, Fleming, & Nichols, 2005; Francis, Thomas, & McGregor, 2001; Nadarajah et al., 2017).

Pre-operative rehabilitation

Pre-operative rehabilitation or “prehabilitation” was first suggested by Noyes, Mooar, Matthews, & Butler (1983) with the aim of restoring knee function before surgery. Noyes et al.'s (1983) suggestion began a trend in this field of research, however there is still a lack of consensus on the effectiveness and necessity of prehabilitation following ACL rupture.

Prehabilitation aims to restore muscle strength and functional capacity following injury as well as preparing the body for a period of immobility and decreased level of activity following surgery (Alshewaier, Yeowell, & Fatoye, 2017; Failla et al., 2016). Additionally, it may increase the effectiveness of post-operative rehabilitation (Alshewaier et al., 2017).

One of the areas that prehabilitation focuses on is quadriceps strength, as this is seen as an important predictor of functional outcome following surgery (Eitzen, Holm, & Risberg, 2009). In their systematic review of 11 studies, Palmieri-Smith, Thomas, & Wojtys (2008) found that deficits in quadriceps strength following ACL reconstruction was common, with rates between 24 and 40.5%. Before Noyes et al.'s (1983) study was released, it was mostly believed that exercise of the quadriceps should actually be restricted before surgery as it was feared that this would cause more damage (Palmieri-Smith et al., 2008). However, since then, research has indicated that the majority of quadriceps exercises are safe to perform as prehabilitation (Beynnon et al., 1995), and actually necessary to maximise function, decrease

knee laxity and decrease recovery time post-operatively (Eitzen et al., 2009; Keays, Bullock-Saxton, Newcombe, & Keays, 2003; Knoll, Kocsis, & Kiss, 2004).

In addition to improving clinical outcomes, in their randomised controlled trial, Shaarani et al. (2013) found an improvement in self-reported function at 12 weeks follow-up after ACL reconstruction with only six weeks of prehabilitation. This finding was important as both literature research and clinical healthcare move towards a more patient-centred approach for outcome measures (Dawson et al., 2010). Additionally, with the prehabilitation time being relatively short at six weeks, it diminished one of the arguments against it, which is that it can increase the injury-to-surgery time period (Hoffmann, Krutsch, & Loose, 2018), a field that is controversial in itself.

Another argument against prehabilitation is that achieving a “quiet knee”, in which the inflammatory response is minimised, before surgery should be prioritised, as this has been shown to decrease arthrofibrosis (Mayr et al., 2004). This is done by minimising irritation, swelling and pain, which may inhibit the knee’s range of motion. Due to rest, ice, compression and elevation having been the conservative treatment guidelines for irritation and swelling for multiple decades (Torburn, 1996), it can be argued that this irritation may be exacerbated by the movement required by prehabilitation. However, a cohort study performed by Failla et al. (2016) which included over 2000 participants found that providing patients with prehabilitation rather than just achieving a quiet knee resulted in significantly better outcomes at a two-year follow-up. These included better IKDC and KOOS scores as well as a higher return to sport (Failla et al., 2016). What may be seen as a limitation within the study was that the type of prehabilitation (e.g. Muscle strengthening or neuromuscular training) was not specified. Therefore, it was not clear which specific type of prehabilitation resulted in better outcomes. In actuality this may be a strength, as it may indicate that the type of prehabilitation does not matter as much as simply having a prehabilitation program in place.

Post-operative rehabilitation

The aim of post-operative rehabilitation is to restore the knee function to pre-injury levels, allow the patient to return to sporting activity and reduce the risk of re-injury and OA (Beynon, Uh, et al., 2005; Hiranyakumar & Karthik, 2015). This is achieved by improving its stability through muscle strengthening (Reiman & Lorenz, 2011), neuromuscular training

(Ingersoll, Grindstaff, Pietrosimone, & Hart, 2008), and proprioception exercises (Liu-Ambrose, Taunton, Macintyre, Mcconkey, & Khan, 2003). Additionally, full range of motion of the knee joint should also be restored to regain functional and dynamic capacity (Arden et al., 2010). The entire ipsilateral and contralateral lower extremities as well as trunk stability are generally focussed on to regain stability (Hiranyakumar & Karthik, 2015).

In the 1980's ACL rehabilitation programs followed a conservative approach, with the suggestion of complete immobilisation of the knee for a period of six weeks to reduce inflammation and allow for graft healing (Paulos et al., 1981). Additionally, it was believed that if the leg was not immobilised in a brace, stability and the integrity of the graft could be compromised (Paulos et al., 1981). However, relatively soon after this study was published, several studies found that immobilisation was harmful to the structures within and surrounding the knee, possibly leading to arthrofibrosis (Beynon et al., 1995; Buckwalter, 1995; Dahlberg, Ryd, Heinegård, & Lohmander, 1992). Around the same time, Shelbourne & Nitz (1992) proposed an accelerated post-operative rehabilitation program. In their study, the authors compared Paulos et al.'s (1981) conservative rehabilitation approach with their accelerated program and found that the latter offered higher patient compliance and satisfaction as well as graft function, less issues with regaining full range of motion and higher levels of strength and overall function.

Current trends of post-operative rehabilitation research reference Shelbourne & Nitz's (1992) accelerated approach and have focused on improving both short and long-term outcomes whilst returning athletes to their respective sports in the shortest period of time possible. Additional areas of focus include reducing the use of restrictive bracing, beginning rehabilitation earlier after surgery (as well as pre-operatively), increasing the intensity whilst reducing the length of time and becoming more cost-effective by decreasing supervision (Grant, 2013).

However, there is still a lack of consensus around this topic, with studies stating that an accelerated rehabilitation program is either no different from a more conservative approach (Beynon et al., 2011), or that it may lead to worse outcomes (Nagelli & Hewett, 2017). Nagelli & Hewett (2017) suggested that an accelerated post-operative rehabilitation approach encouraged young athletes to return to sport too quickly, in particular pivoting and sudden deceleration- heavy sports. These athletes that did follow an accelerated program were at a significantly greater risk of graft-rupture. The authors indicated that biological healing of the

knee was still regularly occurring one year following ACL reconstruction, which was likely to cause deficits in function. Nagelli & Hewett (2017) cautioned a more conservative approach to rehabilitation before returning to sports after a two-year period in an effort to significantly reduce the risk of graft rupture and long-term damage. However, what must be acknowledged is that while Nagelli & Hewett's (2017) study raises awareness of the disadvantages and possible risks around an accelerated rehabilitation program, it is simply not viable for the majority of young competitive athletes to stop participating in their sport for two years due to pressure to return to sport quickly from themselves and their teams (Dingenen & Gokeler, 2017).

Research purposes

ACL rupture is one of the most common ligamentous injuries, and therefore ACL reconstruction is one of the most frequently performed orthopaedic surgeries. Despite this, ACL outcomes measures that suggest failure, including graft rupture, contralateral ACL rupture, graft laxity and long-term OA, are not decreasing. This may be due to a variety of factors, including surgical technique, issues around surgical timing, poor choice of pre- and post-operative rehabilitative strategies and returning to sports too early following surgery.

As indicated in the review above, there is substantial research around the ACL and the many factors that may generate more positive long-term outcomes. However, there are certain areas where little research has been published, one of which is the fixation points for the surgical techniques. Research around this area is of importance, as it may influence techniques used by surgeons, which may benefit patients undergoing ACL reconstruction surgery. To produce the most unbiased results in this area, studies should be conducted using a single surgeon covering multiple techniques that they are reasonably experienced in.

The manuscript below aims to increase this area of research by comparing the long-term outcomes of three different surgical techniques of ACL reconstruction from a single surgeon and surgical centre. The fixation points will be described in depth to increase the usefulness of the results and conclusions drawn from the data.

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Section II: Manuscript

Long-Term Outcomes After Primary Anterior Cruciate Ligament Reconstruction when Comparing Three Surgical Techniques

Abstract

Purpose: To investigate and compare outcomes of three primary ACL hamstring graft reconstruction surgeries. **Methods:** Retrospective analysis of primary ACL reconstructions undertaken by one surgeon between 2006 and 2012 using three techniques of different graft placements and anchors were compared: (1) Single bundle graft at the site of the antero-medial bundle (SB), (2) a double-bundle graft with proximal and distal endobutton fixation (EB), and (3) a double-bundle graft attached in a continuous loop with minimal fixation (MF). The primary outcome measure was ACL graft rupture post-operatively. Secondary outcomes included recurrent rotatory instability, return to sport incidence and time-frame, and patient reported outcome measures (PROMs). **Results:** A total of 216 participants were included (51, 77 and 88 in SB, EB and MF, respectively), 145 (67.1%) male, and aged 30.38 ± 11.63 (mean \pm SD). Patient gender between the three groups was significantly different, 37 (72.5%) male for SB, 58 (75.3%) for EB and 50 (56.8%) for MF ($p = 0.026$). There were 151 (69.9%) cases of concomitant injuries (meniscal or chondral), with meniscal injuries making up 65.7% of these injuries. The rates of meniscal injuries were significantly different between the three surgical groups (72.5%, 67.5% and 53.4% for SB, EB and MF, respectively ($p = 0.046$)). Graft failure occurred in 17 (7.9%) surgeries and did not differ statistically between the three surgical groups ($p = 0.284$) at 8.4 years (SD \pm 2.2) follow-up. At a follow up of 9 years (IQR = 7 – 10), 79.3% of participants felt stable with pivoting movements, with no significant difference between groups ($p = 0.353$). 56.6% of all participants returned to their previous level of sport at median time of 26.00 (IQR = 12.00-42.50) weeks. **Conclusion:** There were no differences in ACL graft rupture rates or patient-perceived stability after more than 8 years follow-up between three primary ACL reconstruction hamstring graft techniques. **Level of Evidence:** Level III

MeSH Keywords: Anterior Cruciate Ligament; ACL reconstruction; hamstring tendon; graft failure; rotatory stability

Introduction

Anterior cruciate ligament (ACL) reconstruction is one of the most frequently performed orthopaedic surgeries. In New Zealand (NZ), 80% of knee ligament surgeries performed between 2000-2005 involved the ACL (Gianotti, Marshall, Hume, & Bunt, 2009). ACL reconstruction is performed to restore stability to the deficient knee and decrease the risk of both subsequent injury and osteoarthritis (OA) within the joint (Kaeding, Pedroza, Reinke, Huston, & Spindler, 2015). Research has indicated that ACL reconstructions are frequently successful in restoring functional knee stability, however negative outcomes such as failure of the ACL graft are relatively common (Schreiber, Eck, & Fu, 2010) (van Eck, Lesniak, Schreiber, & Fu, 2010).

Whilst a rupture of the graft is the most obvious indicator of ACL reconstruction failure, other surgical outcome measures include graft laxity (Sundemo et al., 2018) which may result in rotatory instability (Ayeni, Chahal, Tran, & Sprague, 2012), a failure of return to sport (Paterno, Rauh, Schmitt, Ford, & Hewett, 2014), low scores in patient reported outcome measures (PROMs) (Collins et al., 2016) and early development of OA (Øiestad, Holm, & Risberg, 2018). Factors that influence the risk of ACL graft failure are not clearly understood, with proposed risk factors including graft type and surgical technique (Sajovic, Stropnik, & Skaza, 2018), younger age (Nagelli & Hewett, 2017), levels of activity (high levels increasing risk, particularly with pivoting movements) (Shelbourne, Gray, & Haro, 2009), concomitant injuries (Balasingam, Sernert, Magnusson, & Kartus, 2017; Feucht et al., 2015) pre- and post-operative rehabilitation approaches (Failla et al., 2016; Nagelli & Hewett, 2017) and time between injury and surgery (Nadarajah, Roach, Ganta, Alaia, & Shah, 2017).

Concerning graft selection and technique, there are various factors involved. A single bundle (SB) graft mimics the anteromedial bundle of the ACL (Yasuda et al., 2004). The double-bundle (DB) graft aims to replicate the native ACL and consists of both the anteromedial and posterolateral bundles of the ACL, making it more anatomically accurate. Previous studies have found the DB graft to have better clinical outcomes with an increase in its rotational stability compared to the SB graft which only restores anterior-posterior stability (Desai et al., 2014; Yagi et al., 2002). This may decrease the incidence of OA within the joint (Tashman, Collon, Anderson, Kolowich, & Anderst, 2004). Additionally, Kato et al. (2009) found that a more anatomically placed graft undergoes similar forces to a native ACL, while

a graft that is non-anatomically placed is subjected to greater forces. Both autografts and allografts can be used for ACL reconstruction (Busam, Provencher, & Bach, 2008). Autografts are preferred over allografts due to a lower failure rate, particularly in younger patients, decreased healing time and no risk of disease transmission (Busam et al., 2008; Muramatsu, Hachiya, & Izawa, 2008; Van Eck, Schkrohowsky, Working, Irrgang, & Fu, 2012). Hamstring tendon (HT) grafts consisting of the gracilis and semitendinosus are the most commonly used graft (Muneta et al., 2007), followed by the bone-patella-tendon-bone (BPTB) graft, which typically consists the middle third of the patella tendon and its bone insertion sites on the patella and tibia. Recent research has suggested that HT grafts are preferable to BPTB grafts due to decreased pain at the harvest site, lower incidence of mild radiographic osteoarthritis and decreased postoperative complications and pain.

Despite the amount of research around ACL reconstruction, the surgical techniques involved are usually minimally described. Studies commonly specify whether ACL reconstructions were SB or DB techniques, whether the grafts were allografts or autograft, and whether a HT graft or BPTB graft is used (Kaeding et al., 2015). However, fixation techniques of these grafts are not commonly described, and their failure rates are rarely compared with each other, which limits the application of these studies for surgeons especially.

To improve on the research concerning in-depth surgical techniques, this study appraised three surgical ACL reconstruction techniques that use HT grafts with different fixation techniques with focus on assessing graft rupture rates, patient-reported stability of the knee and PROMs.

Methods

Design

A retrospective review of follow up data from primary ACL reconstruction operations between 16th February 2006 and 13th July 2012 was undertaken between February 2013 and December 2018. The study population consisted of 216 consecutive eligible patients who had received one of the three types of ACL reconstruction techniques undertaken through a single centre: OrthoSports North Harbour Ltd., Auckland, New Zealand; by a single surgeon: Dr Matthew Brick MBChB 1987; FRACS (Orth) 2002. The study consisted of two phases, A and B. For both phases, eligible patient details were extracted from the OrthoSports clinical records and patients were contacted through both email and phone between February 2013 and June 2014 for Phase A and July 2018 and December 2018 for Phase B. Additionally, Phase A participants were re-contacted to gain more recent information.

Participant inclusion and exclusion criteria

Only participants who had received a primary ACL reconstruction on that knee were included. Additionally, the surgery needed to have been performed a minimum of two years before data collection began. Participants were excluded if there was knee ligament rupture other than the ACL on the ipsilateral knee, if they had previous knee ligament surgery or significant malalignment on the ipsilateral knee, or if they had a diagnosis of a concomitant disease that may affect joints.

Reconstruction surgical techniques

All three techniques used hamstring tendon (HT) autografts, two of which were double-bundle and one of which was single-bundle (Appendix A). The single-bundle technique consisted of a graft from both the semitendinosus and gracilis, with the femoral tunnel at the site of the anatomic anteromedial bundle. This technique was abbreviated SB for “single-bundle” within this study. The first double-bundle technique that was used consisted of two hamstring grafts (the anteromedial bundle from the semitendinosus and the posterolateral bundle from the gracilis) and four tunnels drilled in anatomic position. These grafts are attached both proximally on the femur, and distally on the tibia using endobuttons. This technique was abbreviated to EB for “endobutton” within this study. The second double-bundle technique consisted of a continuous graft comprised of both the semitendinosus and

gracilis that was positioned superiorly through the PL tunnel and then looped around and inferiorly through the AM tunnel. It was attached distally on the tibia at a singular fixation point. Both the PL and AM tunnels were drilled in anatomic position. This technique was abbreviated to MF for “minimal fixation” within this study.

Outcome measures

The primary outcome measure was the difference in the incidence of ACL graft rupture between the three surgical techniques. Secondary outcomes focussed on additional measures of success of each surgical technique. These included patient – reported recurrent rotatory instability, return to sport incidence, rehabilitation compliance and PROMs. The PROMs collected in both phases were the Knee Injury and Osteoarthritis Outcome Score (KOOS) questionnaire (Roos, Roos, Lohmander, Ekdahl, & Beynnon, 1998), International Knee Documentation Committee (IKDC) Subjective Knee Form (Anderson, 1994) and the Marx activity scales (Marx, Stump, Jones, Wickiewicz, & Warren, 2001). Additionally, the Tegner activity scale was used in Phase B (Tegner & Lysholm, 1985). An in-house designed online survey was also provided through a Google Docs platform (Auckland, New Zealand) for additional questions for clarification regarding rehabilitation and was used in both phases (Appendix B).

Consent

Within Phase A of this study, ethical approval was sought from the regulatory authority; Health and Disability Ethics Committees (HDEC) (Ministry of Health, 2018). As the study was regarded as a clinical audit, HDEC advised that formal approval was not required (Appendix C). Phase B of this study was approved by Unitec Research Ethics Committee (UREC) 2017 (Appendix D). Additionally, the study met the requirements of Māori locality assessment for the Waitemata and Auckland District Health Board (Appendix E).

Data collection procedures

For both phases, preliminary questions were asked during a phone call and patients were asked whether they wished to participate further with PROMs and clinical assessment. Preliminary questions included side dominance, mechanism of injury, re-injury, degree of trust, providing a rating of overall function, and whether a rehabilitation program was followed. The clinical assessment (Phase A only) consisted of the Lachman’s test (Jain,

Amaravati, & Sharma, 2009), pivot shift test (Jain et al., 2009), anterior-posterior laxity testing with the KT-1000 arthrometer (Goodwillie, Shah, McHugh, & Nicholas, 2017) and provided PROMs as a hard paper copy during clinical visits. Phase B did not include clinical visits; therefore, PROMs were completed online using Standardised Orthopaedic Clinical Research and Treatment Evaluation Software (SOCRATES) (Socrates Ortho trading under Ortholink Pty Ltd, Pyrmont, NSW, Australia).

Due to the long – term follow – up, a number of potential participants’ contact details were no longer correct, making it difficult to contact these individuals. Due to this, a review of operation and subsequent clinical notes and appointments was undertaken for all participants. If an individual could not be contacted, the data collected from this review was used concerning subsequent graft rupture, re-injury and re-operation with the assumption that the individual or their medical health practitioner would have relayed this information back to the surgical centre as is customary.

Statistical analysis

Sample size

The sample size required for the study was estimated based on the differences in two independent proportions (for graft rupture rates) (Select Statistical Services, 2019) and for differences in changes in IKDC score using G Power (Faul, Erdfelder, Lang, & Buchner, 2007). Estimates of 73 participants per technique group were obtained for detecting a difference in proportion of 5% compared to 20% between groups for graft rupture rate (Select Statistical Services, 2019). Estimates of 64 per group were obtained for detecting an effect size of 0.5 (Faul et al., 2007), equating to a difference in IKDC score of approximately 8 (of 100 total points) (Sonnery-cottet et al., 2017). Both estimates assumed a level of significance of 0.05 and a statistical power of 0.8. A target of 65-80 participants per group was deemed ideal for the study.

Data analysis

Data were analysed using Excel Version 16.21.1 (Microsoft Corporation (MS), Redmond, WA, USA) and IBM SPSS Statistics 25 (IBM, Armonk, NY, USA) and the level of significance (p-value) set at 0.05 for all statistical tests. Differences between techniques in graft rupture rates and the rates of other categorical variables were assessed using Chi Square analysis. Between-technique differences in PROMs and other continuous variables were

analysed using Kruskal-Wallis non-parametric statistical tests, since these data breached assumptions of normality.

Results

SB surgeries were undertaken between 16th February 2006 and 13th June 2012, EB between 11th July 2006 and 14th October 2009, and MF between 29th July 2008 and 2nd May 2012. There were 51 (Phase A = 44, Phase B = 7) participants in the SB group, 77 (Phase A = 70, Phase B = 7) in the EB group and 88 (Phase A = 79, Phase B = 9) in the MF group.

Of the 216 participants, 145 (67%) were male (Table 1). Patient gender between the three groups was significantly different $X^2 (2, N = 216) = 7.263, p = 0.026$ (Table 1). The median age at the time of injury was 27 years (inter-quartile range (IQR) = 19 – 37), with 28 years (IQR = 20 – 38) being the median age at surgery. The median injury to surgery time was 24 (IQR = 14 – 42) weeks. Only 18 of the 87 (21%) of the participants asked reported a family history of ACL injury. Distribution of ACL reconstructions were similar when comparing left and right knees, with 105 (49%) participants having reconstructive surgery on the right.

Table 1. Surgical technique group comparison: Patient demographics and injury mechanism.

	SB	EB	MF	Total	p
Age at injury (y)	31, 21-39 (51)	27, 19-38 (76)	24, 18-35 (88)	27,19-37(125)	.052
Gender (male)	73% (37)	75% (58)	57% (50)	67% (145)	.026
Dominant side (R)	88% (21)	84% (27)	98% (40)	91% (88)	.128
Family history	13% (3)	8% (2)	33% (13)	21% (18)	.029
Injury side (R)	53% (27)	52% (40)	43% (38)	49% (105)	.414
Injury during sports	94% (17)	96% (25)	96% (46)	96% (88)	.960
Non-contact injury	73% (10)	62% (16)	68% (32)	67% (58)	.621
Cartilage damage	35% (18)	30% (23)	34% (30)	33% (71)	.775
Meniscal damage	73% (37)	68% (52)	53% (47)	63% (136)	.046
Any concomitant damage	80% (41)	71% (55)	63% (55)	70% (151)	.080

Key:

Continuous data (age at injury) is median, IQR (n); Categorical (dichotomous) data percentage of respondents (n)

Abbreviations: years (y); right (R)

Injury characteristics

Age at injury did not differ significantly between surgical technique groups $H(2) = 5.909, p = 0.52$ (Table 1). Additionally, time interval between injury and surgery in weeks did not significantly differ between the groups, and age at surgery was also not significantly different (Table 1).

Most ACL injuries resulted from a non-contact mechanism (58 of 86 (67%)). Of the 92 participants asked, 88 (96%) injuries reportedly occurred during recreational or competitive sports participation. There were no significant differences between surgical technique groups for these variables (Table 1).

The overall proportion of concomitant injuries (meniscal or cartilaginous) was 70% (151/216). This variable did not significantly differ between the three graft techniques (Table 1). Most of the concomitant injuries were meniscal, and these were statistically different between surgical technique groups $X^2 (2, N = 216) = 6.144, p = 0.046$ (Table1).

Surgical characteristics

Whilst the ACL reconstruction was performed, 113 of 172 participants (65.7%) underwent an additional surgical procedure(s). These were not statistically significant between groups (Table 2). The median time that the tourniquet was tied was 75 (IQR = 65 – 85) minutes, and this was significantly different between groups (Table 2).

Table 2. Surgical technique group comparison: Surgical considerations

	SB	EB	MF	Total	P
Age at surgery (y)	34, 22-41 (47)	28, 20-39 (73)	25, 13-41 (78)	28,20-38 (198)	.057
Injury-surgery time (w)	21, 14-40 (47)	26, 17-54 (72)	22, 13-14 (78)	24,14-42 (197)	.229
Tourniquet time (m)	67, 60-75 (47)	82, 74-91(74)	75, 68-80 (88)	75,65-85 (209)	<.001
Other procedures	57% (29)	56% (43)	47% (41)	52% (113)	.375

Key:

Continuous data (age at injury) is median, IQR (n); Categorical (dichotomous) data percentage of respondents (n)

Abbreviations: years (y); weeks (w); minutes (m)

Post-surgery characteristics

Overall, 17 (8%) participants experienced a graft rupture, while 37 (17%) experienced a re-injury to the ipsilateral knee, including meniscal, chondral, or ligament damage. There was no significant difference in ACL graft rupture proportion between the three surgical technique groups $X^2 (2, N = 216) = 2.519, p = 0.284$. In addition, there were no differences of knee re – injury between the three groups (Table 3).

The median re-rupture time and re-injury time were 0.6 years (IQR = 0.8 – 2.2) and 1.3 years (IQR = 0.6 – 2.7), respectively. From the entire sample, 34 (16%) participants were reoperated on with a median time of 1.3 year (IQR = 0.8 – 2.6). These times were not significantly different between surgical technique groups (Table 3). The median follow-up time concerning re-injury and subsequent surgery was 9 years (IQR = 7 – 10). This varied between the surgical technique groups, with the MF group having the shortest follow-up and the EB group having the longest follow-up period $H(2) = 61.960, p = <0.001$ (Table 3).

When asked, 69 of 87 participants (79%) said that they trusted their knee, which was statistically significant between surgical technique groups $X^2 (2, N = 87) = 7.910, p = 0.019$ (Table 3). When asked whether they felt stable when twisting/pivoting, 23 of 29 (79%) participants said they did, with no significant differences between groups (Table 3). The current self-reported overall median knee rating was 8/10 (IQR = 7 – 9) and did not differ significantly between the three surgical technique groups (Table 3).

Table 3. Surgical technique group comparison: Post-surgery outcome measures

	SB	EB	MF	Total	P
Rate (0-10)	7, 6-9 (24)	8, 6-10 (21)	8, 8-9 (31)	8, 7-9 (76)	.091
Graft rupture time (y)	0.6, 0.5- (3)	0.7, 0.5-1.9(4)	0.4,0.7-3.1(10)	0.6,0.8-2.2(17)	.181
Re-injury time (y)	0.8, 0.5-1.7(7)	1.6,0.6-2.6(8)	1.4,0.7-3.2(12)	1.3,0.6-2.7(180)	.725
Re-op time (y)	1.2,0.9-2.6(12)	0.9,0.7-2.5(8)	1.8,0.9-3.4(14)	1.3,0.8-2.6(216)	.505
Follow-up re-injury (y)	9,7-12 (51)	10,9-11 (77)	8,7-8 (88)	9, 7-10 (216)	
Trust	67% (16)	70% (16)	93% (37)	79% (69)	.019
Pivot trust	67% (8)	100% (1)	88% (14)	79% (23)	.353
Graft rupture	6% (3)	5% (4)	11% (10)	8% (17)	.284
Re-injury	27% (10)	21% (7)	25% (20)	17% (37)	.059
Re-op	24% (12)	10% (8)	16% (14)	16% (34)	.136

Key:

Continuous data (age at injury) is median, IQR (n); Categorical (dichotomous) data percentage of respondents (n)

Abbreviations: years (y)

Patient reported outcome measures (PROMs)

The mean follow-up time concerning PROM scores was 6.3 (SD ± 2.9) years. This varied between the surgical technique groups $H(2) = 12.435, p = 0.002$ (Table 4).

The median IKDC scores were 87.4/100 (IQR = 72.7 – 94.3). See Table 4 for median values of all PROMs with IQR. The only scores that were significantly different between the three surgical technique groups were KOOS function in daily living $H(2) = 9.945, p = 0.007$ and function in sport and recreation $H(2) = 7.502, p = 0.023$ (Table 4).

Table 4. Surgical technique group comparison: Patient Reported Outcome Measures

	SB	EB	MF	Total	P
KOOS pain	92, 83-98 (22)	97,90-100(29)	92,86-100(39)	94,86-100(90)	.069
KOOS symptoms	82, 64-93 (23)	89, 82-98 (29)	86, 75-96 (39)	86,75-96(91)	.123
KOOS (ADL)	96,90-100(23)	100,97-100 (29)	100, 94-100 (39)	100,94-100(91)	.007
KOOS (sport/rec)	80, 70-95 (23)	95, 88-100 (29)	100, 94-100 (39)	90,75-100(91)	.023
KOOS (QOL)	63, 44-88 (23)	88, 66-100 (29)	85,69-99 (36)	81,63-100(88)	.052
IKDC	77, 62-87 (23)	91, 74-97 (36)	87, 83-93 (49)	87,73-94(108)	.072
Tegner	5, 4-6 (5)	6, 3-7 (24)	7, 6- (2)	6, 4-7 (31)	.481
Marx	7, 1-11 (19)	9, 3-12 (35)	12, 6-12 (19)	9, 3-12 (73)	.55
Follow-up scores (y)	7, 6-9 (23)	6, 5-10 (36)	6, 3-7 (53)	12, 3-24 (112)	.002

Key:

Continuous data (age at injury) is median, IQR (n); Categorical (dichotomous) data percentage of respondents (n)

Abbreviations: years (y); function in daily living (ADL); function in sport and recreation (sport/rec); quality of life (QO)

Gender Differences

There were no statistically significant differences between females and males in any of the data variables collected, excepting two. The median time from ACL reconstruction to re-operation was 3.4 years for females (IQR = 1.6 – 4.7) and 1.1 years for males (IQR = 0.8 – 2.0), $H(1) = 4.104, p = 0.043$. However, the time periods between primary ACL reconstruction and both re-rupture and re-injury were not significantly different between genders, $p = 0.070$ and $p = 0.294$, respectively (Table 5). For the 17 patients who

experienced a graft re-rupture, the median time interval between graft rupture and re-operation was 0.3 years for males and 0.8 years for females. Additionally, the rates of re-rupture, re-injury or re-operation were not significantly different $p = 0.393$, $p = 0.356$ and $p = 0.387$, respectively (Table 5).

The second variable that was different between genders were the KOOS function in sport and recreation scores. From a maximum score of 100, the median for females was 85 (IQR = 60 – 99) and the median for males was 95 (IQR = 80 – 100), $H(1) = 5.775$, $p = 0.016$.

Table 5. Gender comparison concerning graft injuries, ruptures and re-operations

	Male	Female	Total	P
Graft rupture time (y)	0.8, 0.5-1.4 (13)	2.6, 1.1-3.3 (4)	0.8, 0.6-2.2 (17)	0.070
Re-injury time	1.3, 0.5-2.0 (21)	2.6, 0.6-3.5 (6)	1.3, 0.6-2.8 (27)	0.294
Re-op. time	1.1, 0.8-2.0 (19)	3.4, 1.6-4.7, (5)	1.3,0.9-2.6 (24)	0.043
Graft rupture	9.0% (13)	5.6% (4)	7.9% (17)	0.393
Re-injury	22.4% (28)	16.4% (9)	21.6% (37)	0.356
Re-op.	17.2% (25)	12.7% (9)	15.7% (34)	0.387
Other proc.	50.3% (73)	56.3% (40)	52.3% (113)	0.407

Key:

Continuous data (age at injury) is median, IQR (n); Categorical (dichotomous) data percentage of respondents (n)

Abbreviations: years (y); procedures (pro)

Rehabilitative characteristics

When reporting rehabilitation compliance, 84 of 89 (94%) participants reported participating in either a guided or non-guided rehabilitation program. Rehabilitation guided by a physiotherapist or equivalent trainer was reported by 57 of 62 (92%) participants. The median duration of this guidance was 12 weeks (IQR = 8 – 24). The median patient-reported compliance was 9 (IQR = 6 – 10) on a scale from 0-10, 0 being not participating in any rehabilitation, and 10 being following a rehabilitation program completely. Rehabilitation guidance, duration or compliance was not significantly different between surgical technique groups (Table 5).

Level of pre- and post-injury activity was not significantly different between the three graft types, with participants scoring a median score of 6/10 (IQR = 4 – 7) on the Tegner Activity

Score and a median score of 9/16 (IQR = 3 – 12) on the Marx Activity Score (Table 4). When asked whether they had returned to their previous level of sport, 35 of 62 (57%) individuals said yes. The median overall time to return to sports was 26 weeks (IQR = 12 – 43). This was not significantly different between groups (Table 5). Time to return to sports was also not significantly different between the three graft types (Table 5). Some reasons for not returning to their previous sport included participants feeling “too old”, work and family commitments, changing sports, other injuries and loss of confidence and trust.

Table 6. Surgical technique group comparison: Rehabilitation and return to sports

	SB	EB	MF	Total	P
Rehab compliance	8, 7-10 (23)	8, 5-10 (23)	9, 7-10 (40)	9, 6-10 (86)	.557
Rehab timing (w)	11, 7-21 (8)	10, 6-24 (19)	16, 11-26 (21)	12, 8-24 (58)	.246
RTS fc sports (w)	0, 0-23 (20)	0, 0-46 (21)	12, 0-38 (21)	0, 0-32 (62)	.524
RTS lc sports (w)	22, 0-45 (20)	26, 9-52 (21)	26, 20-36 (21)	26, 12-40 (62)	.524
RTS any sport (w)	22, 0-45 (20)	28, 11-52 (21)	26, 20-36 (21)	26, 12-43 (62)	.323
Rehab participation	92% (22)	92% (22)	98% (40)	94% (84)	.069
Rehab guidance	90% (18)	86% (18)	100% (21)	92% (57)	.219
RTS	55% (11)	43% (9)	71% (15)	57% (35)	.173

Key:

Continuous data (age at injury) is median, IQR (n); Categorical (dichotomous) data percentage of respondents (n)

Abbreviations: weeks (w); return to sport (RTS); full contact (fc); limited contact (lc)

Discussion

Graft rupture

The primary aim of this study was to investigate the differences in graft rupture rates between three different surgical ACL reconstruction techniques. The graft rupture rates were not statistically different between the three groups ($p = 0.284$). The lack of significant differences could be due to insufficient numbers of failures to detect a statistical difference between the three surgical groups (216 participants with 51, 77 and 88 in SB, EB and MF, respectively). The study was powered to detect a graft rupture rate of 20% compared to 5%. As the overall percentage of graft rupture was 8%, ranging between 5% (EB), 6% (SB) and 11% (MF), there is no statistically significant difference. Assuming that these rates were indicative of true graft rupture rates, a sample size of 318 per group would have been required for the largest difference between groups to be statistically significant (Select Statistical Services, 2019).

It is also possible that both graft make-up (single-bundle versus double-bundle) and anchoring technique may not be indicative of graft failure rates. If that were the case, it may suggest that rather than using a specific graft technique thought to be the most advantageous, it may be more appropriate for surgeons to choose the technique based on other factors such as their own experience, patient demographics and intended use of the knee following reconstruction.

Conversely, the lack of significant differences could be due to insufficient numbers of failures to detect a statistical difference between the three surgical groups (216 participants with 51, 77 and 88 in SB, EB and MF, respectively). The study was powered to detect a graft rupture rate of 20% compared to 5%. As the overall percentage of graft rupture was 8%, ranging between 5% (EB), 6% (SB) and 11% (MF), there is no statistically significant difference. Assuming that these rates were indicative of true graft rupture rates, a sample size of 318 per group would have been required for the largest difference between groups to be statistically significant (Select Statistical Services, 2019).

As mentioned, a larger cohort may have possibly led to significant differences between the three surgical technique groups when comparing graft rupture rates. However, the sample size was limited to the number of ACL reconstructions that the surgeon had performed within

a particular time-frame to maintain long-term follow-up. Additionally, as mentioned previously, due to the long-term follow-up, a number of potential participants could not be contacted as their contact information was now incorrect. Due to this, data collected from their operation and subsequent clinical notes was used within this report. Therefore, some data was collected with the assumption that we had the most-up to date information, however there is a chance that participants may have not informed the surgical centre of certain updates.

A cohort of patients from several surgeons within either the same centre or different centres could have been used. However, this may have possibly affected results due to surgeon technique preference and experience, as it has been suggested that surgeon technical error is a primary determinant of reconstruction success (Busam et al., 2008; Morgan, Dahm, Levy, & Stuart, 2013; Wright et al., 2010). Morgan et al. (2013) cited “technical cause of error” as the reason behind 48% of graft failures, the majority of which were femoral malposition. This was corroborated by Trojani et al. (2011) who cited femoral malposition as the primary reason for 36% of graft failure cases. Therefore, collecting a cohort of patients from more than one surgeon could have possibly led to multiple scenarios: The surgeons’ usual preference and therefore proficiency with respect to technique may have been dictated by either their training in a particular technique or awareness of the literature around technical causes of error accounting for large numbers of ACL graft failure in several studies. Alternatively, if general surgical experience and proficiency varied between surgeons with different preferences for technique, differences in graft failure rates due to technique may be obscured by differences between surgeons.

Trust

Whether participants trusted their knee following their ACL reconstruction was significantly different between surgical technique groups ($p = 0.019$). While only 68% and 70% of the SB and EB surgical technique groups trusted their knee, 93% of the MF surgical technique group trusted their knee. Although they compared two different techniques for drilling the femoral hole during ACL reconstruction, Rahr-Wagner, Thillemann, Pedersen, & Lind (2013) published a prospective study comparing two surgical techniques, one of which was more anatomically accurate. The authors found that the technique which imitated the anatomy of the native ACL more closely had a higher re-rupture rate. To explain this finding, Rahr-Wagner et al. (2013) referred to a laboratory study by Xu et al. (2011) which demonstrated

that an anatomically placed anteromedial bundle of an ACL graft was placed under significantly higher load than an anteromedial bundle that was located more superiorly than the native ACL. While this is a plausible explanation, it is also possible that an anatomically placed ACL may feel less artificial to the patient in a shorter time-span following surgery. This could lead to an increase in trust of the operated knee and accelerate return to activities subjecting the knee to high load and thus the risk of graft rupture. Here, the highest level of trust was observed with the MF surgical technique, which is the most anatomically accurate technique of the three. Although we observed no significant differences between the three surgical groups in terms of graft rupture, the observed rate for the MF group was highest (at 11%), indicating a possible link with the higher level of trust. The theory that a high level of trust, which is normally a good outcome, could possibly be connected to higher rates of graft rupture has not previously been raised in the literature, and may be something to consider in future research.

Gender

There were two statistically significant differences between males and females within the data collected. One of the differences that was significant was the median time period from ACL reconstruction to any re-operation, $p = 0.043$: 3.4 years for females and 1.1 years for males. Although the time period between primary ACL reconstruction and graft rupture was itself not significantly different between genders, $p = 0.070$, there is a possible trend in the same direction. Since there were only 17 graft ruptures observed in this study, only very large differences between genders in the time between surgery and graft rupture would have been statistically significant. By comparison, there were 24 secondary operations performed on the cohort, which may have increased the statistical power for detecting a significant difference. The median time between graft rupture and re-operation, for the 17 patients who re-ruptured, was 0.3 years for males, and 0.8 years for females. As females had a possible trend of later graft ruptures as well as significantly later re-operation times overall, it may indicate that there is less urgency around ACLs and females in several ways. Firstly, it is possible that females do tend to rupture their grafts at a later time, which could possibly indicate that they may take longer to load the graft after surgery. Additionally, a possibly longer graft tear to re-operation time may indicate that females have less urgency in returning to sport, as one of the main reasons for a short injury to surgery time is the goal of a rapid return to sport (Evans, Shaginaw, & Bartolozzi, 2014).

Limitations

There were several limitations within this study. Firstly, as discussed, the sample size was small, which could have affected the statistical significance of a proportion of results. The cohort was restricted due to a limited number of operations performed using each of the three techniques as the surgeon's preferred technique changed throughout the period that data was collected from. In addition to the small cohort, the follow-up rate was inconsistent amongst the variables, due to these being collected through various means (telephone, email, review of clinical notes and hard copies).

Additionally, the researchers could not be blinded to the surgical technique groups. Therefore, researcher bias cannot be ruled out as there were several points of contact that the researchers could have influenced results through suggestive wording on emails or influencing subjective answers through the phone calls. Reduction of bias was attempted by the use of PROMs which were pre-established with a validated scoring system and completed by patients with no interference from the researchers.

With regard to possible bias, this study was partially funded by OrthoSports North Harbour Ltd., Auckland, New Zealand, of which Dr Matthew Brick is a major shareholder, the director and a senior surgeon. All of the participants were extracted from his list of patients. Additionally, the primary supervisor, Dr Catherine Bacon, is also a research employee at the surgical centre. These factors could produce skewed results, as it could be argued that an employee would endeavour for their place of employment to be presented in the best possible light, and so therefore wish to highlight certain findings that do this. However, as failure rates of the ACL reconstructions were not compared to another surgeon or surgical centre, the risk of bias is decreased.

Conclusion

Within this study, no significant differences were found in graft rupture rates between surgical technique groups. Rotatory stability was also not significantly different between surgical technique groups. However, a significantly higher number of participants in the MF surgical technique group trusted their knee, which was the most anatomically correct surgical technique. Further studies assessing surgical techniques in terms of graft composition and graft fixation will be necessary to determine whether there is a difference in graft rupture rates, including specifying more and less anatomically correct techniques.

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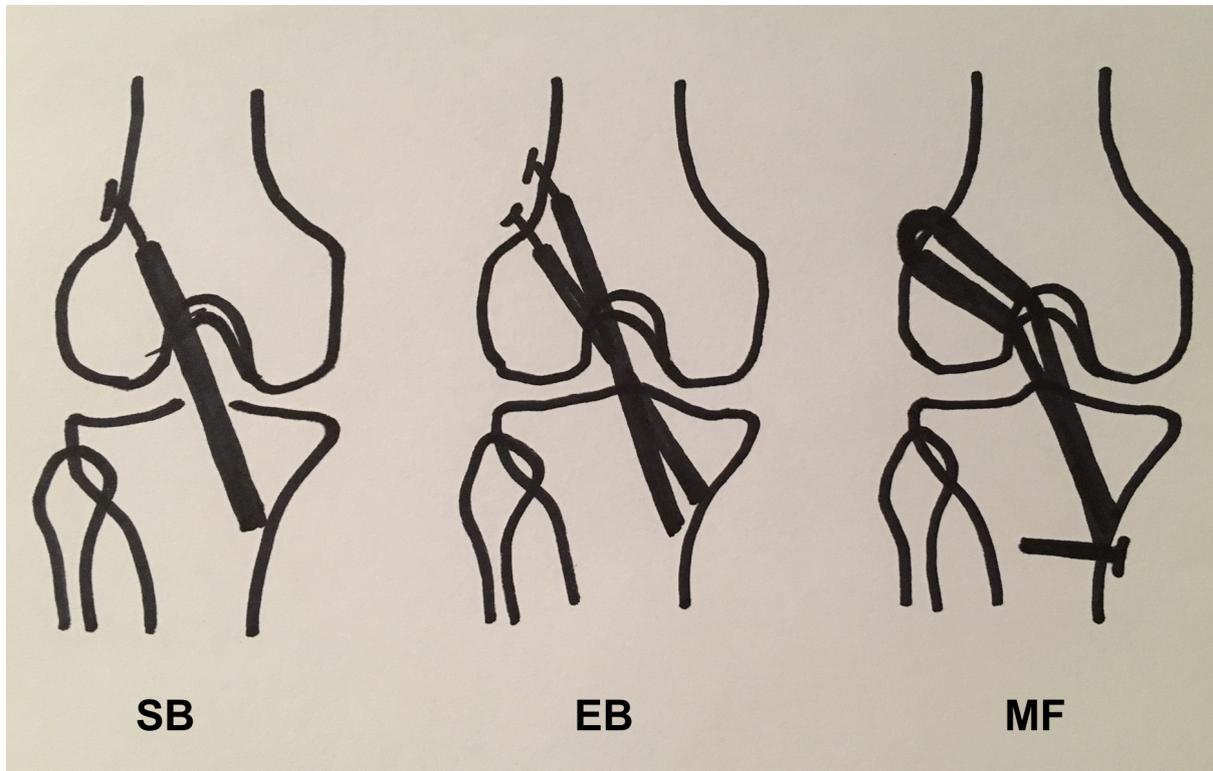
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Appendix A: Schematic diagram of the three ACL reconstruction surgical techniques



Abbreviations: SB, single bundle, one graft from semitendinosus and gracilis with the femoral tunnel at the site of the anteromedial bundle; EB, endobutton, two hamstring grafts (the anteromedial bundle from the semitendinosus and the posterolateral bundle from the gracilis) and four tunnels drilled in anatomic position that are attached both proximally on the femur and distally on the tibia using endobuttons; MF, minimal fixation, a continuous graft comprised of both the semitendinosus and gracilis that was positioned superiorly through the PL tunnel and then looped around and inferiorly through the AM tunnel, attached distally on the tibia at a singular fixation point, with both tunnels drilled in anatomic position.

Appendix B: In-house designed online survey (relevant questions)



Q6A. Did you follow a rehabilitation (rehab) program after your first ACL surgery?

- Yes (Dr Brick's rehab program)
- Yes (but not Dr Brick's program) -> please also tick "Other" and specify details
- No rehab program
- Other...

Q6B. Did you see a physiotherapist or equivalent trainer to help with your rehab at that time?

- Yes
- No

Q6C. How long did you see a physiotherapist and/or trainer for your rehab after your first ACL surgery? (Please specify total number of weeks (E.g. 26), only write the number.)

Q6D. How well did you complete your rehab program after your first ACL surgery?

Did NO rehabilitation 0 1 2 3 4 5 6 7 8 9 10 Did ALL rehabilitation possible

Q7A. Did you return to your previous level of sport after your first ACL surgery rehabilitation?

- Yes
- No

Q7B. If you did not return to your previous level of sport, please specify the reason(s)? (Select all choices appropriate, and/or specify in "Other")

- Age
- Work
- Changed sport
- Knee didn't recover after ACL surgery
- Other injuries
- Other...

Q8A. How long after your first ACL surgery did you return to full contact* sports?

(Please specify total number of weeks (E.g. 26), only write the number.) No or never = 0.

*Full contact sport = rugby league, rugby union, Australian rules football, lacrosse, roller derby, American football, water polo, sumo, team handball, slamball, ice hockey and full contact martial arts such as mixed martial arts, jujutsu, Muay Thai, judo and full contact karate etc.

8B: How long after your first ACL surgery did you return to limited contact* sports?

(Please specify total number of weeks (E.g. 26), only write the number.) No or never = 0.

*Limited contact sport = baseball, football (soccer), basketball, field hockey, netball, Korfbal, squash, running and ultimate frisbee etc.

Appendix C: Health and Disability Ethics Committees (HDEC) letter



Health and Disability Ethics Committees
1 The Terrace
C/- MEDSAFE, Level 6, Deloitte House
10 Brandon Street
PO Box 5013
Wellington
6011

0800 4 ETHICS
hdec@moh.govt.nz

31 October 2013

Doctor Matthew Brick
Millennium Institute
17 Antares Place
Mairangi Bay
Auckland 0632

Dear Doctor Brick

Re:	HDEC ref:	13/CEN/170
	Study title:	An observational study of the failure rate of anterior cruciate ligament reconstruction: a comparison of three different arthroscopic techniques.

Thank you for submitting your application for HDEC review on 31 October 2013. The Secretariat has assessed the information provided in your application and supporting documents against the Standard Operating Procedures.

This application has not been validated, as on the basis of the information you have submitted, it does not appear to be within the scope of HDEC review. This scope is described in section three of the *Standard Operating Procedures for Health and Disability Ethics Committees*.

An audit or related activity requires HDEC review only if it involves the use, collection or storage of human tissue without consent, other than in accordance with a statutory exception (set out at section 20(f) of the [Human Tissue Act 2008](#) and Right 7(10)(c) of the [Code of Health and Disability Services Consumers' Rights 1996](#)).

If you consider that our decision not to validate this application is in error please contact us as soon as possible giving reasons for this.

This letter does not constitute ethical approval or endorsement for the activity described in your application, but may be used as evidence that HDEC review is not required for it.

Please don't hesitate to contact us for further information.

Yours sincerely,

A handwritten signature in black ink, appearing to read "Nic Aagaard".

Nic Aagaard
Administrator
Health and Disability Ethics Committees

Appendix D: Unitec Research Ethics Committee (UREC) letter of approval



December 12 2017

Dear Franca Bauer,

Your file number for this application: **2017-1083**

Title: **An observational study of the failure rate of anterior cruciate ligament reconstruction: a comparison of three different arthroscopic techniques – Phase II**

Your application for ethics approval has been reviewed by the Unitec Research Ethics Committee (UREC) and has been approved for the following period:

Start date: December 12 2017

Finish date: December 12 2018

Please note that:

1. The above dates must be referred to on the information AND consent forms given to all participants.
2. You must inform UREC, in advance, of any ethically-relevant deviation in the project. This may require additional approval.

We wish you every success with your project.

Yours sincerely,

A handwritten signature in black ink, appearing to read 'N. Adams'.

Nigel Adams
Deputy Chair, UREC

cc: Asher Lewis

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Appendix E: Waitemata and Auckland District Health Board (DHB) letter of approval

22 October 2013

Dr Johan Smalberger
Millennium Institute of Sport and Health
17 Antares Place
Private Bag 302-145, NHMC
Auckland 0751

Re: Failure of anterior cruciate ligament reconstruction techniques (at least) two years after surgery.

The purpose of this letter is to provide support for the above study. Dr Smalberger and Dr Mathew Brick have met with me in the development of the study protocols and the participant information and consent forms. The study seeks to compare failure rates between knee reconstruction surgeries to see which has the better success rate and therefore outcomes for participants.

The investigators have provided an inequality analysis demonstrating that there may be approximately 6% (14/240 to 18/300) Māori participants in the study. They also acknowledge there is likely to be no difference in knee reconstruction failure between Maori and others.

The investigators have met the requirements of a Māori locality assessment for the Waitemata and Auckland District Health Board and therefore I am happy to support this study.

Please note a Maori Research Review critiques research proposals for responsiveness to Maori. Ethical, scientific and clinical rigour is reviewed by the relevant bodies.

Heio ano

H. A. Wihongi

Dr Helen Wihongi | Maori Research Advisor
He Kamaka Waiora | Waitemata and Auckland DHB

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SUBMISSION OF THESIS/DISSERTATION/RESEARCH PROJECT FOR EXAMINATION

Please complete the form and submit to the Postgraduate Office along with the required copies of your research for examination. (Please email the Postgraduate Academic Administrator (Cynthia Almeida) ahead of time when you will be dropping off your thesis [email: calmeida@unitec.ac.nz](mailto:calmeida@unitec.ac.nz) /Phone 0212095265 (Mob)

PART A: (To be filled in by student)

Full Name:	FRANCA BAUER	Student ID Number: 1431866
Programme:	MOst.	Enrolment Status: Semester <i>(Student should be enrolled when submitting thesis for examination)</i>
Email Address:	franca@bauer.org.nz	Telephone No: 02102353211
Postal Address:	111 EDGERLEY RD, RDI, WARKWORTH 0981	
Thesis Title:	long term outcomes after primary Anterior Cruciate Ligament reconstruction when comparing three surgical techniques	

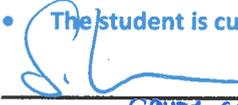
I have advised my Primary Supervisor that I am submitting my thesis for examination Yes/No

Principal Supervisor: CATHERINE BALON Associate Supervisor: JOHAN SMALBERGER

Student Name: FRANCA BAUER Student Signature

Part B: CONFIRMATION BY THE ACADEMIC LEADER

- The version of the Thesis/Research Project that is here being submitted has been checked using 'Turnitin' and the Academic Leader is satisfied that appropriate standards of scholarship have been met.
- The student is currently enrolled.

 Academic Leader SYLVIA KACH (Signature)
course coordinator

PART C: RECEIPT OF THESIS BY RESEARCH OFFICE

This confirms receipt by the Research Office and Postgraduate Centre, of the required soft bound copies of your thesis/ dissertation/ research project and the digital version, for examination.

Date of receipt: 20/2/19 Postgraduate Academic Administrator.....  (Signature)

Notes on examination process:

- 1) For research in Design, Architecture, and Landscape Architecture, the written document will be sent for examination by a panel and an oral examination will be scheduled in the coming weeks. Please contact your Academic Leader/Administrator for information regarding the date time and location of this part of the examination process.
- 2) For all other degrees (MBus, MIC, MOst, MEdLM, MEd, MSocP, Mcomp, MAP) the submitted documents will be sent to examiners as soon as suitable examiners have been assigned. Examiners are normally given four weeks to provide their grade recommendation. Please note that for the examination process the responsibility of the Research Office commences at the point of receipt of the 'request for examiners' from the Academic Leader and not from the date of submission of the thesis by the student. Research grades are approved by the Dean of Research and Enterprise. In cases of disparity between recommended grades a process of consultation is initiated with examiners to determine whether a closer agreement may be reached. If this is not possible the research may be sent to a third examiner for adjudication. In such cases the length of time required for examination can be longer.
- 3) Please note that even when recommending high grades examiners often require changes or amendments to be made prior to submission of the final hard bound copies. In the uncommon event of a student's work being failed, students are given three months to resubmit for re-examination on a pass/fail basis (e.g. C- or D).
- 4) The above information should be taken into account by students when considering timelines for graduation or making commitments in relation to employment that depend upon degree completion.



Declaration

Name of candidate: Franca Bauer

This Thesis/Dissertation/Research Project entitled: Long-Term Outcomes After Primary Anterior Cruciate Ligament Reconstruction when Comparing Three Surgical Techniques.

is submitted in partial fulfillment for the requirements for the Unitec degree of Master of Osteopathy (M.Ost).

Principal Supervisor: Catherine Bacon

Associate Supervisor/s: Johan Smalberger

CANDIDATE'S DECLARATION

I confirm that:

- This Thesis/Dissertation/Research Project represents my own work;
- The contribution of supervisors and others to this work was consistent with the Unitec Regulations and Policies.
- Research for this work has been conducted in accordance with the Unitec Research Ethics Committee Policy and Procedures, and has fulfilled any requirements set for this project by the Unitec Research Ethics Committee.

Research Ethics Committee Approval Number:

Candidate Signature: Franca Bauer Date: 19/02/2019

Student number: 1431866

Full name of author: FRANCA BAUER

ORCID number (Optional):

Full title of thesis/dissertation/research project ('the work'):

LONG-TERM OUTCOMES AFTER PRIMARY
ANTERIOR CRUCIATE LIGAMENT
RECONSTRUCTION WHEN COMPARING THREE
SURGICAL TECHNIQUES.

Practice Pathway: SCHOOL OF COMMUNITY STUDIES

Degree: MASTER OF OSTEOPATHY

Year of presentation: 2019

Principal Supervisor: CATHERINE BACON

Associate Supervisor: JOHAN SMALBERGER

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Date: 19.1.02.2019