USING THE VERT WEARABLE DEVICE TO MONITOR JUMPING LOADS IN ELITE VOLLEYBALL ATHLETES

by

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Using the VERT wearable device to monitor jumping loads in elite volleyball athletes

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Abstract

Sport is evolving into a more competitive industry, leaving athletes prone to injuries. Monitoring athletes using wearable technology provides a way to potentially manage training and competition loads with the goal of reducing injuries. One such technology is the VERT, a commercially available discrete wearable device that measures vertical displacement from the center of mass. While several studies have examined the accuracy of the VERT's measures of jump height and jump count, landing impact has not yet been investigated. The objective of this research study was to explore the potential utility of the VERT as a load monitoring tool in elite volleyball players. This was done by (1) examining the accuracy of the VERT landing impact values in university volleyball players and (2) retrospectively analyzing a VERT data set collected over the course of a university volleyball season, documenting whether established relationships were observed between various load characteristics and knee pain. We hypothesized that the VERT landing impact values would fall within 10% of those derived from a research-grade accelerometer, the Shimmer. In the data set, we expected to see agreement with the literature in that acute:chronic workload ratio (ACR), average jump height, jump count and session rating of perceived exertion (sRPE) were positively associated with knee pain. We also expected knee pain to increase over the course of the season and for leftsides/middle blockers to report the highest pain. Methodology for the validation study included recruiting 14 players, having each perform 10 jumps while wearing both devices. For the retrospective analysis, we used linear mixed effect modelling. The results of the validation showed that VERT landing impacts were variable (limits of agreement of -84.13% and 52.37%) and had a propensity to be lower (mean bias of -15.88%) when compared to the Shimmer. In the retrospective analysis, average jump height ($p=0.041$) and date ($p=0.032$) were negatively associated with knee pain (however the associations were of small magnitude). In conclusion, the validity of the VERT device's landing impact values are generally poor, with respect to Shimmer. The relationships in the data set were partially consistent with what previous literature has shown.

Lay Summary

The goal was to explore the utility of a wearable device, the VERT, for monitoring jumping loads in elite volleyball players. This was done by (1) examining the accuracy of the VERT landing impact values in university volleyball players and (2) analyzing a past VERT data set collected over the course of a university volleyball season.

The results of part one showed that VERT landing impacts were variable and had a tendency to be lower when compared to a research-grade accelerometer. In part two, increases in the ratio of acute to chronic workload and jump count were related to increases in knee pain. Additionally, as average jump height and days into the season increased, knee pain decreased.

The VERT may be a useful tool to monitor and manage jumping loads during training and competition, although the parameter of landing impact may not be truthful and caution should be exercised with its interpretation.

Preface

This thesis is original work by the author, Faraz Damji, under the supervision of Dr. Alex Scott with guidance from Dr. Michael Hunt, Dr. Kerry MacDonald and Dr. Jack Taunton.

The study procedures were performed according to the guidelines of the Clinical Research Ethics Board at the University of British Columbia. The Clinical Research Ethics Board Certificate Number is H19-00163.

Study protocol and documents were developed by Dr. Alex Scott and Faraz Damji, with the assistance of Dr. Michael Hunt, Dr. Kerry MacDonald and Dr. Jack Taunton. Statistical analysis was completed by Eric Sanders and Nikolas Krstic, under the direction of Faraz Damji and supervision of Dr. Alex Scott.

To date, the findings present in this thesis have not been published.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

ACR	Acute:chronic workload ratio
AIC	Akaike Information Criterion
CCC	Concordance correlation coefficient
CMJ	Countermovement jump
EWMA	Exponentially weighted moving average
ICC	Intraclass correlation coefficient
IMU	Inertial measurement unit
MCAR	Missing completely at random
OSTRC-P	Oslo Sport Trauma Research Centre-Patellar Tendinopathy
RA	Rolling average
RPE	Rating of perceived exertion
SD	Standard deviation
Shimmer	Shimmer3 Inertial Measurement Unit
sRPE	Session-rating of perceived exertion
WG	War Memorial Gym

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I am deeply grateful to Dr. Alex Scott, my supervisor, for allowing me to pursue my MSc program under his esteemed tutelage. He provided invaluable guidance and feedback in a very timely manner which I truly appreciated. His empathetic style of communication and consistent enthusiasm for my project really propelled me to stay highly focused throughout this project. Dr. Scott's efforts have unearthed in me a passion for scientific inquiry and inspired me to actively pursue research alongside my future career.

I express my profound admiration and respect to the supervisory committee members - Dr. Michael Hunt, Dr. Kerry MacDonald, and Dr. Jack Taunton - for playing an integral role at every step of the research process and helping to create a collegial environment.

I am especially indebted to Dr. Taunton for his selfless mentorship throughout my post-secondary education and his unwavering belief in my potential.

I would also like to acknowledge the efforts of Eric Sanders, Nikolas Krstic and Johann Windt for assisting with the statistical analysis, and to David Gil for his expert advice on the VERT wearable technology.

Finally, I was fortunate to be the recipient of a CIHR Canada Graduate Scholarship Master's Award, which provided funding for this study.

Dedication

To my parents, thank you for instilling in me the value of lifelong learning. You have supported me throughout my years of education, both morally and financially. I am deeply grateful for your endless love, support, sacrifice and encouragement.

Special thanks also to my brother Samir, thank you for always helping me strive to be the best version of myself.

Chapter 1: Introduction

1.1 Overview

Athletes today are being exposed to high training loads and saturated competition calendars, due to the evolving nature of sport into a more competitive and professionalized industry. This creates an environment that is conducive to sports injuries. For example, tendinopathy is an overuse injury to the tendon and is associated with chronic tendon pain (Scott et al., 2013). This condition occurs at a variety of anatomic locations (shoulder, Achilles, knee, elbow, hip, etc.), and is commonly observed in individuals who subject their tendons to high mechanical loads (Scott et al., 2013). The underlying tissue pathology demonstrates a failed healing response characterized by collagen degeneration and remodeling, neurovascular proliferation, increased presence of leukocytes, inflammatory stromal fibroblast activation, and increased glycosaminoglycans (Scott, Backman, & Speed, 2015). The end-result of this pathophysiology is a swollen, painful tendon caught in a cumulative cycle of injury-repair which can last months or years (Attia et al., 2014). People with tendinopathy are typically advised to scale back the intensity of their sports participation while they participate in rehabilitation, and then gradually increase tendon loading activities whilst monitoring pain (Peter Malliaras, Cook, Purdam, & Rio, 2015).

The idea of "load management" is emerging and gaining more attention. Evidence supports that poor load management is a major risk factor for injury (Soligard et al., 2016). In the context of sports medicine, load can be defined broadly as "the sport and non-sport burden (single or multiple physiological, psychological or mechanical stressors) as a stimulus that is applied to a human biological system (including subcellular elements, a single cell, tissues, one or multiple organ systems, or the individual)" (Soligard et al., 2016). Additionally, it may be applied "over varying time periods (seconds, minutes, hours to days, weeks, months and years) and with varying magnitude (ie, duration, frequency and intensity)" (Soligard et al., 2016).

Monitoring training and competition load placed on athletes is gaining popularity as a fundamental practice to ensure they are being subjected to appropriate and therapeutic levels (Bourdon et al., 2017). A new generation of wearable technologies are available, which enable the precise quantification of load with built-in accelerometers, gyroscopes and magnetometers. One such technology is the VERT system (www.myvert.com), a commercially available discrete wearable device that measures vertical displacement from the center of mass of an athlete through a proprietary algorithm (Charlton, Kenneally-Dabrowski, Sheppard, & Spratford, 2017) (Figure 1.1). This inertial measurement unit (IMU) contains a 3-axis accelerometer, 3-axis gyroscope and 3-axis magnetometer. The dimensions of the unit are 6 x 3 x 0.5 cm and it is typically worn on an elastic belt at the level of the L3 or L4 vertebrae, thought to be near the body's center of mass. The basic model records jump count and jump height and a newer G-VERT model also records landing impact and kinetic energy. Potential benefits of the G-VERT include the low cost relative to similar IMUs, non-invasive nature, minimal discomfort, wireless connectivity to an iOS application, ability to wear in game or practice, quick set up, data collection in real-time, and social sharing feature. The limitations include short battery life, limited range, and lack of studies investigating accuracy; also, it may offer too much personal health data to its users leading to information overload. Over 350 colleges, professional and Olympic teams worldwide are using VERT technology, including many Division 1 volleyball programs, USA Volleyball, and the Miami Heat of the NBA (www.myvert.com/testimonials).

Figure 1.1 VERT system and VERT elastic waistband.

Several studies have examined the accuracy of the VERT's measures of jump height and jump count, and generally shown it to be acceptable (Borges et al., 2017; Brooks, Benson, & Bruce, 2018; Charlton et al., 2017; MacDonald, Bahr, Baltich, Whittaker, & Meeuwisse, 2017; Mahmoud, Othman, Abdelrasoul, Stergiou, & Katz, 2015; Manor, Bunn, & Bohannon, 2018; C. Skazalski, Whiteley, Hansen, & Bahr, 2018; Staiger & Wahl, 2018). Interestingly, one study comparing the VERT to a switch mat found that the jump heights were consistently 10 cm apart, concluding that the VERT is reliable but not recommended for practical use (McDonald, 2017). Landing impact, however, is a key parameter that has not yet been investigated. In sport, the act of landing from a jump is often required and may happen very frequently (McNitt-Grey JL, 1991). The resulting ground reaction forces on the body during landing have been shown to be influential in lower limb injury (Nigg, 1985). It is apparent that the movement of joints and muscle activity in the lower limb can decrease the magnitude of these impact forces. The VERT calculates landing impact as the instantaneous acceleration values resulting from forces upon landing, expressed as a G-force (1G = 9.81m/s^2). A resultant value is given, encompassing all components of acceleration in the X-Y-Z axes. This study was the first to perform an external validation of VERT for the landing impact parameter.

Additionally, we conducted a pilot examination of player data from a male varsity volleyball team that has implemented the VERT system, and examined the data set for completeness, presence of artefacts, and whether the data showed expected trends. It was anticipated that the load characteristics of sRPE, ACR, average jump height, and jump count would be positively associated with knee pain (Helland et al., 2013; Timoteo et al., 2018; H. Visnes & Bahr, 2013). Furthermore, we expected knee pain to increase over time, as the season progressed (Helland et al., 2013; H. Visnes & Bahr, 2013). We expected that those who played the leftside and middle blocker positions would be the players with the highest knee pain (Bahr & Bahr, 2014; Mahieu et al., 2011). Although it has been shown in the literature that these associations exist, our understanding is still evolving and there is a need for further research attention to strengthen the evidence. Moreover, we do not know exactly how these load characteristics as well as other predictors relate to injury (Christopher Skazalski, Whiteley, & Bahr, 2018).

1.2 Patellar Tendon Structure, Function, and Adaptation

1.2.1 Patellar Tendon Structure

Tendons are connective tissues that connect muscle to bone, and serve to transmit forces generated by muscles to move and stabilize joints (J. H. C. Wang, 2006). Tendons are structured in a hierarchical manner with collagen molecules, fibrils, fiber bundles, fascicles and tendon units that run parallel to the long axis of the tendon (Figure 1.2) (J. H. C. Wang, 2006). Separating the components are the endotenon and epitenon, thin sheaths of connective tissue that contain blood vessels, nerves and lymphatics (Kastelic, Galeski, & Baer, 1978). A third, outermost layer called the paratenon envelopes the tendon and reduces friction with adjacent tissue (Schatzker & Brånemark, 1969). This multi-unit hierarchy affords tensile strength and creates a “crimp pattern” when viewed in a microscope (Stouffer, Butler, & Hosny, 1985; J. H. C. Wang, 2006).

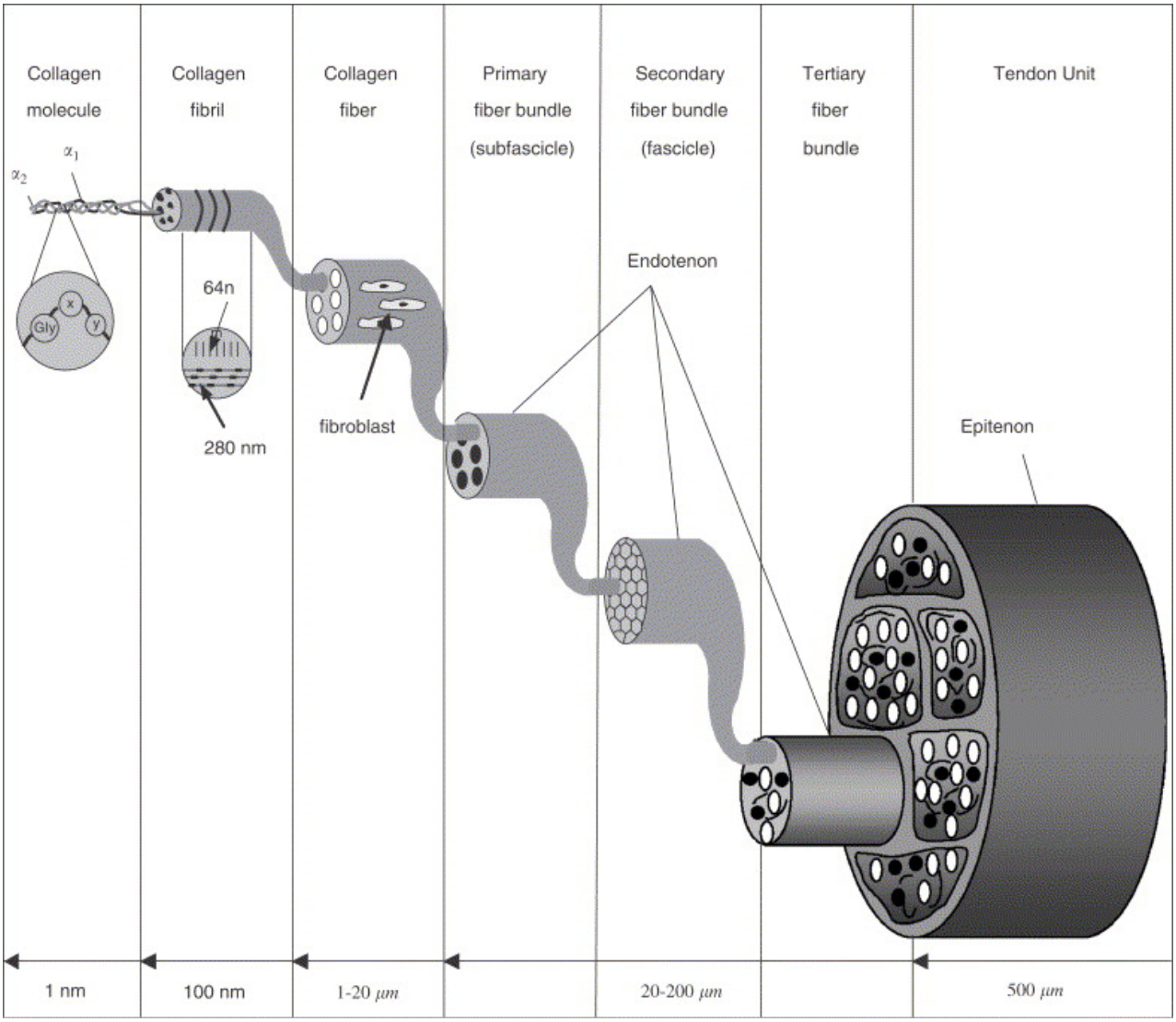

Figure 1.2: Illustration of the multi-unit hierarchical structure of the tendon (Wang, 2006, reproduced with permission).

A healthy tendon is rich in collagens, with type I collagen being the most abundant. It may constitute approximately 60% of the tendon dry mass and 95% of the total collagen (Evans & Barbenel, 1975; Riley et al., 1994). Tendons also consist of proteoglycans, glycoproteins, cells and water. Tenocytes, elongated fibroblast type cells, are the most dominant cell type and are

organized between collagen fiber bundles (J. H. C. Wang, 2006). These cells are responsible for producing the extracellular matrix and an organized collagen matrix (J. H. C. Wang, 2006).

The patellar tendon is located just below the kneecap, and attaches the distal aspect of the patella (either anteriorly, inferiorly, or posterior surface of apex) to the tibial tubercle on the tibia (Basso, Johnson, & Amis, 2001; Palastanga, Field, & Soames, 1998). Given that it connects two bones, it is sometimes referred to as the patellar ligament. The tibial and patellar attachment sites, or entheses, differ in structure from the tendon itself and are characterized by a transitional zone of tissue with 4 components – fibrous connective tissue, uncalcified fibrocartilage, calcified fibrocartilage and bone (Benjamin & Ralphs, 1997). It is thought that fibrocartilaginous entheses have a mechanical role, diffusing forces and reducing wear and tear (Benjamin & Ralphs, 1997). The patellar tendon is a continuation of the quadriceps tendon that arises from the quadriceps, derived mostly from the central fibers of the rectus femoris that pass anteriorly over the surface of the patella (Andrikoula, Tokis, Vasiliadis, & Georgoulis, 2006). In a study conducted to measure the length of the patellar tendon in normal adults, the mean tendon length was 42.6 mm with a range from 30 mm to 60 mm (Choi et al., 2010). In terms of bundle orientation, the fascicles are parallel in the sagittal plane but converge in the frontal plane toward their tibial insertion, such that the tendon is thin and broad proximally, becoming thick and narrow distally (Basso et al., 2001). The anterior and posterior aspects of the patellar tendon can be observed in Figures 1.3 – 1.4 (Basso et al., 2001).

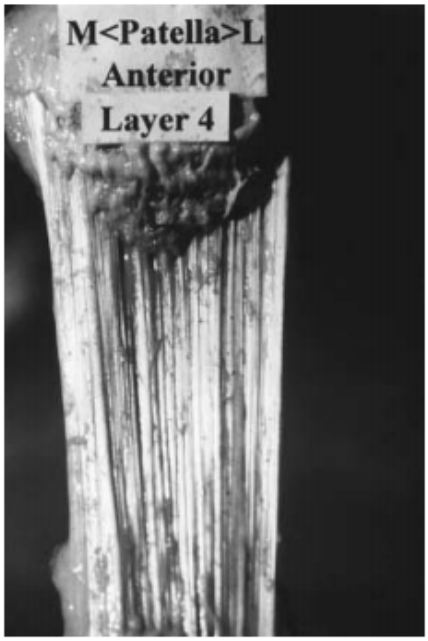

Figure 1.3 Anterior aspect of the patella and patellar tendon, displaying the crescent-shaped line of attachment (Basso et al., 2001, reproduced with permission).

Figure 1.4 Posterior aspect of the patella and patellar tendon (Basso et al., 2001, reproduced with permission).

1.2.2 Patellar Tendon Function

The patellar tendon is an essential component of the knee extensor mechanism. The force generated from the quadriceps muscles acts through the quadriceps tendon and patellar tendon as a pulley, causing the knee to extend or straighten (Palastanga et al., 1998). The force required for knee extension depends directly on the perpendicular distance between the patellar tendon and the axis of rotation at the knee, or the moment arm of the knee joint (Fox, Wanivenhaus, & Rodeo, 2012). The patella acts as a fulcrum and increases this moment arm, improving the efficiency of the quadriceps (Fox et al., 2012). During in-vivo weight-bearing flexion, uniform deformation of the patellar tendon has been observed (DeFrate et al., 2007). The length of the tendon increased significantly between full extension and 30°, and remained constant between 30° and 110° (DeFrate et al., 2007). Changes from anterior to posterior orientation as well as a decrease in the medial orientation of the tendon were also found with flexion (DeFrate et al., 2007).

A study by Johnson et al. (1994) analyzed the tensile and viscoelastic properties that contribute to the unique mechanical behavior of the human patellar tendon in younger donors (29-50 years old) and older donors (64-93 years old). Viscoelasticity is defined by a sensitivity to different strain rates; tendons are more deformable at low strain rates and less deformable at high strain rates (J. H. C. Wang, 2006). Therefore, more energy is absorbed at low strain rates but tendons become stiffer and more effective in transmitting large muscular loads to bone at high strain rates (J. H. C. Wang, 2006). The ultimate tensile strength and strain at failure, respectively, were 64.7 ± 15.0 MPa and 14 ± 6% for younger donors and 53.6 ± 10.0 MPa and 15 ± 5% for older donors (Johnson et al., 1994). The Young's modulus, a measure of a material's ability to withstand changes in length when under longitudinal stress (i.e. stiffness), was 660 ± 266 MPa and 504 ± 222 MPa for the younger and older groups, respectively (Johnson et al., 1994).

Although studies have indicated minimal differences in biomechanical properties of the patellar tendon among age groups (Carroll et al., 2008; Couppé et al., 2009; Johnson et al., 1994), other studies have revealed that properties can be altered by the processes of maturation and ageing (Hsiao, Chen, Lin, Chen, & Wang, 2015; Kubo, Teshima, Hirose, & Tsunoda, 2014; McCrum et al., 2018; O'Brien, Reeves, Baltzopoulos, Jones, & Maganaris, 2010). A greater mechanical stiffness due to an increased Young's modulus in adults compared to children has been found in the elderly (Kubo et al., 2014; O'Brien et al., 2010), but also reduced patellar tendon elasticity with aging (Hsiao et al., 2015; McCrum et al., 2018).

With respect to sex effects on patellar tendon mechanical properties, findings are equivocal in that one study concluded that stiffness is correlated and affected by sex (Taş et al., 2017), while another study ruled out the influence of sex (Burgess, Pearson, Breen, & Onambélé, 2009). This discrepancy may be the result of different age groups being tested, and the changing hormonal milieu during the aging process. Tendon has been shown to contain estrogen receptors responsive to female sex hormones, which could affect tendon stiffness (Hart et al., 1998; Uldbjerg & Ulmsten, 1990). The study by Taş et al. (2017) also did not examine individuals' amount of daily activity, which might be another factor affecting patellar tendon mechanical properties, whereas the study by Burgess et al. (2009) ensured the sampled populations were similar in terms of activity levels.

1.2.3 Patellar Tendon Responses to Loading and Training

It has been demonstrated that in response to exercise-related loading, human tendons undergo biochemical changes including increases to tendon blood flow (Boushel et al., 2000; H. Langberg, Boushel, Skovgaard, Risum, & Kjær, 2003), uptake of glucose (Bojsen-Møller, Kalliokoski, Seppänen, Kjaer, & Magnusson, 2006; Kalliokoski et al., 2005), collagen turnover (Henning Langberg, Rosendal, & Kjær, 2001; Miller et al., 2005), expression of structural and regulatory genes (Sullivan et al., 2009; Trappe et al., 2008), inflammatory mediators (Henning

Langberg, Olesen, Gemmer, & Kjær, 2002), and growth factors and related binding proteins (Heinemeier, Langberg, Olesen, & Kjaer, 2003; Olesen et al., 2007). These metabolic changes presumably contribute to altered physical properties of the tendon.

Nine to twelve weeks of resistance exercise training induces significant patellar tendon hypertrophy, in a region-specific manner (Kongsgaard et al., 2007; Seynnes et al., 2009). It has been suggested that the increase in cross-sectional area serves as a protective mechanism to reduce stress on the tendon (Kongsgaard et al., 2007). Increases in patellar tendon stiffness and modulus generally occur as well, but this seems to depend on the load-intensity and contraction type, with more adaptations at or above 80% of concentric 1RM and when high load eccentric contractions are performed (Peter Malliaras, Kamal, et al., 2013). More habitual and chronic exercise training induces even greater region-specific hypertrophy of the patellar tendon (Couppé et al., 2008). In older individuals, although studies suggest that the adaptability of the patellar tendon to exercise may be attenuated, it is still unclear and more studies are needed (Carroll et al., 2011; Reeves, Maganaris, & Narici, 2003; Standley et al., 2013).

Although tendons may exhibit positive adaptations to the functional demands placed on them, negative changes can occur when excessive load is placed on tendons. The cumulative effect of small, repetitive strains below the failure threshold of a tendon can lead to tendon overuse injuries, collectively referred to as tendinopathy (Khan, Cook, Kannus, Maffulli, & Bonar, 2002). Tendinopathy affects millions of people in both athletic and occupational settings (Almekinders, Baynes, & Bracey, 1995). “Overuse” implies repetitive stretching of a tendon, resulting in the inability of the tendon to withstand further tension (Jozsa & Kannus, 1997). Cook and Purdham (2009) described a continuum model of tendon pathology with three distinct stages, to explain the clinical presentation of load-induced tendinopathy (Figure 1.5). The first stage, called reactive tendinopathy, is characterized by an increase in tendon cross-sectional area, but without tendon stiffening that is part of the normal response to load (Cook & Purdam, 2009). The second stage, called tendon disrepair, can be distinguished by greater matrix breakdown, protein production, and disorganization of collagen (Cook & Purdam, 2009). Additionally, there may be

an increase in vascularity and neuronal growth (Cook & Purdam, 2009). The third stage, called degenerative tendinopathy, is hallmarked by areas of cell death due to apoptosis or trauma (Cook & Purdam, 2009). There is little collagen remaining and pathological changes are suggested to be irreversible at this stage (Cook & Purdam, 2009). In a study by Tran et al. (2020), new insights are provided into the early phase of patellar tendinopathy development in humans, suggesting that tendinopathy pathogenesis represents a disrupted tissue homeostasis. It was demonstrated that in the first three months of tendinopathy, there is an increase in anterior-posterior diameter accompanied by hypervascularization and tissue anabolic signaling, along with increased expression of a nociceptive signal substance (Substance P) (Tran et al., 2020). No change in tendon mechanical properties was detected at this early stage of the condition (Tran et al., 2020).

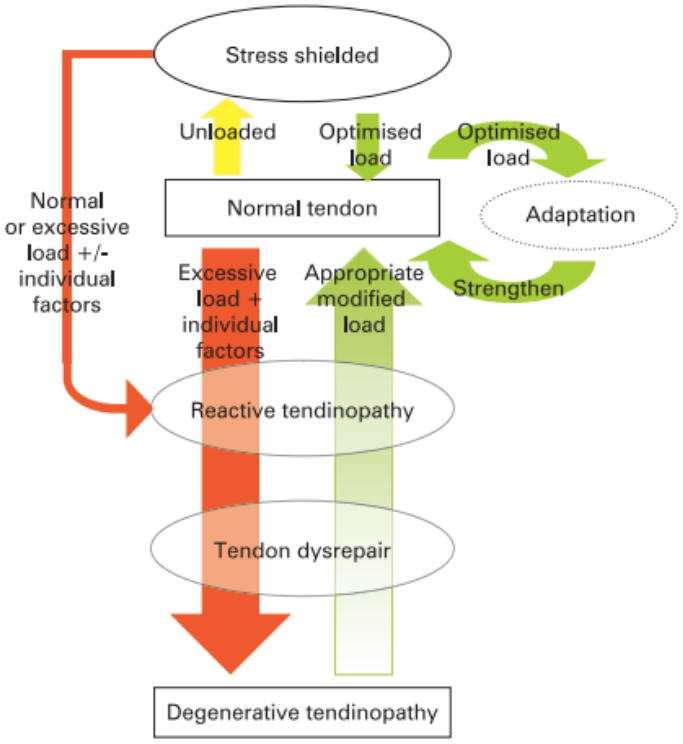

Figure 1.5 Tendon pathology continuum (Cook & Purdam, 2009, reproduced with permission).

1.3 Prevalence of Patellar Tendinopathy

Studies have examined the prevalence of patellar tendinopathy in athletes and shown that it depends heavily on the type of sport performed, with rates being the highest in jumping athletes who place great demands on the leg extensors.

In a study of recreational athletes the overall prevalence was 8.5%, and prevalence was highest in volleyball players (14.4%) and lowest in soccer players (2.5%) (Zwerver, Bredeweg, & Van Den Akker-Scheek, 2011). In a study of elite athletes, the overall prevalence was substantially higher compared to non-elite at 14.2% (Ø. B. Lian, Engebretsen, & Bahr, 2005). Volleyball (44.6% ± 6.6%) and basketball (31.9% ± 6.8%) exhibited the highest prevalence whereas no cases were observed in cycling and orienteering (Ø. B. Lian et al., 2005). In both studies, jumper's knee was approximately twice as common in male athletes compared with female athletes (Ø. B. Lian et al., 2005; Zwerver et al., 2011). Elite male volleyball players therefore comprises a special population that is very prone to the disorder with a prevalence of 40% to 50% (Ferretti, Ippolito, Mariani, & Puddu, 1983; Ferretti, Papandrea, & Conteduca, 1990; Ø. Lian, Holen, Engebretsen, & Bahr, 2008). In the workplace rather than the athletic setting, there are certain occupations at higher risk of developing patellar tendinopathy, such as policemen and fire-fighters (Tiemessen, Kuijer, Hulshof, & Frings-Dresen, 2009).

1.4 Risk Factors for Patellar Tendinopathy

The relationship between painful patellar tendinopathy and the underlying tendon pathology is unclear, but it appears that they are independent of each other. For example, although pain is often associated with pathological tendons, tendon pain in seemingly normal patellar tendons has been demonstrated (Peter Malliaras & Cook, 2006). On the contrary, patellar tendon pathology observed via ultrasound imaging may be present in individuals who are asymptomatic (P.

Malliaras, Cook, Ptasznik, & Thomas, 2006). Therefore, several studies have examined the extrinsic and intrinsic risk factors for both patellar tendinopathy and pathology.

The most common factor that is linked with the onset of patellar tendinopathy is an increase in training volume and frequency (Janssen, Steele, Munro, & Brown, 2014; H. Visnes & Bahr, 2013). Other extrinsic factors that may have an effect include the surface density and the amount of shock absorption in both the shoes and the surface (Rudavsky & Cook, 2014). Intrinsic factors that appear to be associated with patellar tendinopathy include high bodyweight, high BMI, large abdominal circumference, leg length discrepancy, low foot arch height, weak quadriceps, and poor quadriceps and hamstrings flexibility (Van Der Worp et al., 2011).

Individual biomechanics, including movement kinetics and kinematics, may influence patellar tendinopathy risk as well (Peter Malliaras & O'Neill, 2017). It has been shown that horizontal landings are associated with greater patellar tendon force than vertical landings (S. Edwards et al., 2012). Further, participants with asymptomatic patellar tendon pathology landed in more knee flexion and had a stiffer knee landing strategy in horizontal landing compared to their counterparts with normal patellar tendons (Suzi Edwards et al., 2010).

1.5 Diagnosis and Treatment of Patellar Tendinopathy

Patellar tendinopathy is one of many diagnoses producing anterior knee pain. Other diagnoses associated with anterior knee pain include patellofemoral pain, pathology of the fat pad, patellar subluxation, and Osgood-Schlatter disease (Calmbach & Hutchens, 2003). Patellar tendinopathy, however, has two defining clinical features that consist of (1) pain localized to the inferior pole of the patella and (2) load-related pain that increases with the demand on the knee extensors, notably in activities that store and release energy in the patellar tendon (Peter Malliaras et al., 2015). Pain is rarely experienced at rest and occurs with the onset of loading in a dose-dependent manner, as the magnitude or the rate of application of the load on the tendon becomes greater

(Peter Malliaras et al., 2015). A key clinical test is the single-leg decline squat, in which the patient is instructed to stand on a 25 degree decline board and squat to achieve maximum knee flexion, while pain is simultaneously recorded on a visual analogue scale (Figure 1.6) (Rudavsky & Cook, 2014). The affected leg is compared to the unaffected leg. When it comes to imaging the patellar tendon, pathology may be observed in asymptomatic individuals, and symptoms often improve without changes in imaging pathology (Peter Malliaras et al., 2015). However, imaging can still be helpful for diagnosis confirmation, especially if the loading tests are equivocal or if the site of tenderness on palpation cannot be pinpointed (Scott et al., 2013). The specificity and sensitivity of MRI (82% and 57%, respectively) and gray scale ultrasonography (82% and 87%, respectively) in confirming clinically diagnosed patellar tendinopathy has been evaluated (Warden et al., 2007).

Figure 1.6 Single-leg decline squat (Rudavsky & Cook, 2014, reproduced with permission).

Management of this condition generally involves a conservative approach. The fundamental principles include decreasing the load in order to reduce pain, followed by a gradual and individualized exercise progression to improve tendon capacity (Rudavsky & Cook, 2014). Pain levels should be frequently monitored throughout the rehabilitation phase (Rudavsky & Cook, 2014). The most investigated intervention for patellar tendinopathy is eccentric exercise (Peter Malliaras, Barton, Reeves, & Langberg, 2013). Although it has been shown that eccentric

exercise is effective and superior to other interventions such as concentric exercise, recent studies have supported heavy slow resistance training as a potentially better intervention and isolating the eccentric component may not be of greater benefit than combined loading programs (Jonsson & Alfredson, 2005; Kongsgaard et al., 2009; Peter Malliaras, Barton, et al., 2013). An evidence-based 4-stage rehabilitation progression was proposed by Malliaras et al. (2015) (Figures 1.7 and 1.8). Passive techniques may be useful in augmenting an exercise or loading program, however the evidence shows a lack of effect for these interventions alone (Rudavsky & Cook, 2014). Examples of these forms of treatment are cryotherapy, patellar counterforce straps, nonsteroidal anti-inflammatory drugs, corticosteroids, sclerosing injections, platelet-rich plasma, extracorporeal shock wave therapy, glyceryl trinitrate patches, and low-intensity pulsed ultrasound.

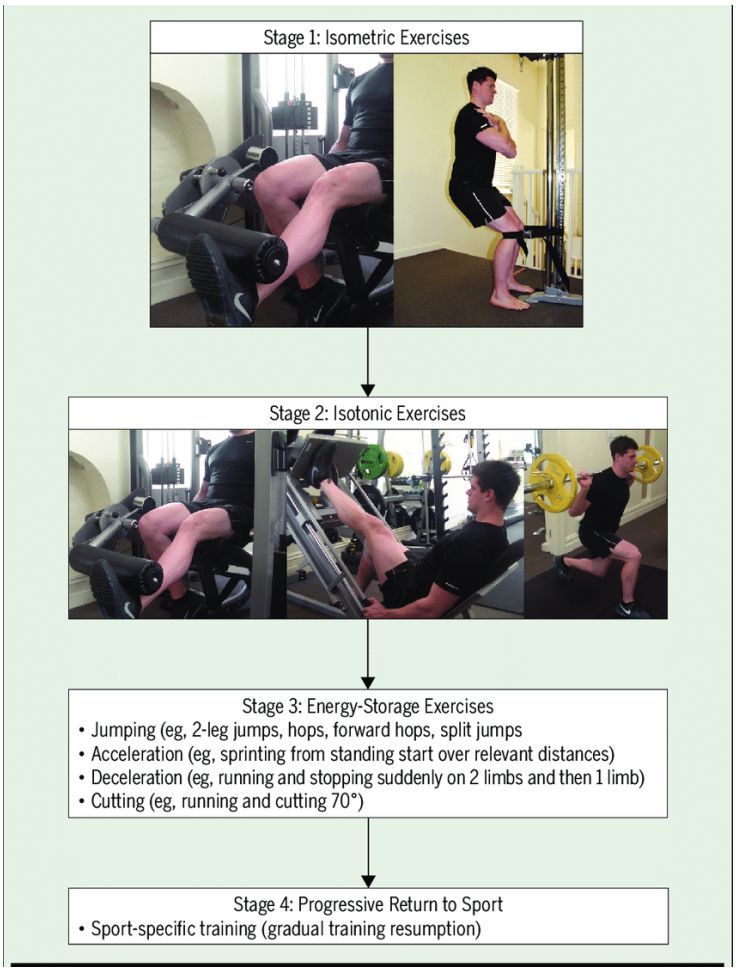

Figure 1.7 Progression of patellar tendinopathy rehabilitation (Peter Malliaras et al., 2015, reproduced with permission**).**

TABLE **Rehabilitation Stages and Progression Criteria**

Stage	Indication to Initiate	Dosage
1. Isometric loading	More than minimal pain during isotonic exercise*	5 repetitions of 45 seconds, 2 to 3 times per day; progress to 70% maximal voluntary contraction as pain allows
2. Isotonic loading	Minimal pain during isotonic exercise*	3 to 4 sets at a load of 15RM, progressing to a load of 6RM, every second day; fatiguing load
3. Energy-storage loading	A. Adequate strength† and consistent with other side B. Load tolerance with initial-level energy-storage exercise (ie, minimal pain during exercise and pain on load tests returning to baseline within 24 h)*	Progressively develop volume and then intensity of relevant energy-storage exercise to replicate demands of sport
4. Return to sport	Load tolerance to energy-storage exercise progression that replicates demands of training	Progressively add training drills, then competition, when tolerant to full training

Abbreviation: RM, repetition maximum.
**Minimal pain defined as 3/10 or less.*
†For example, around 150% body weight (4 × 8) for most jumping athletes.

Figure 1.8 Rehabilitation stages and progression criteria (Peter Malliaras et al., 2015, reproduced with permission).

1.6 Wearable Sensor Technology

The external (mechanical load placed on an athlete) and internal (physiological or psychological response to imposed demands) loads on athletes, as well as other health related parameters, are being measured to an increasing level of precision by wearable sensors (Düking, Achtzehn, Holmberg, & Sperlich, 2018). There exists a range of different types of wearable sensors, including IMUs and microelectromechanical sensors, containing a combination of accelerometers, magnetometers and gyroscopes (Adesida, Papi, & McGregor, 2019). These

devices can also be found embedded in textiles, watches and patches located on or near the body (Sperlich, Aminian, Düking, & Holmberg, 2020). Rising research and interest into this technology is helping to improve our understanding of their potential applications, and although there seems to be potential for wearable sensors in sports, they are still in an exploratory phase and it is currently unclear to what extent they will be useful (Sperlich et al., 2020).

There are several possible advantages to using wearable sensors. Perhaps the most conspicuous of which is that they could be employed in field settings (not restricted to a laboratory environment) to provide coaches with objective (kinetic and kinematic variables), real-time feedback on the performance of their athletes (Adesida et al., 2019). As a result, the data could be used for a multitude of purposes based on the interests of the coaching staff: (1) to measure, control and increase the physical performance of players, (2) to prevent injuries that are caused by overloading, (3) to prevent too-early return-to-play of injured players, and (4) to monitor and forecast performance development of younger players. Furthermore, wearable sensors are designed to function in any sporting environment due to their small, lightweight, wireless and unobtrusive design (Adesida et al., 2019). Some have the added features of being waterproof or being able to record data in cold temperatures (Bächlin & Tröster, 2012; Krüger & Edelmann-Nusser, 2009).

Despite the numerous benefits offered by wearable sensors, there are certainly disadvantages to consider as well. Peake et al. (2018) conducted a critical review of consumer-grade wearables, mobile applications, and equipment designed to provide biofeedback to physically active individuals. These investigators concluded that only 5% of the technologies they reviewed have been formally validated through independent research and that manufacturing companies should invest in research to prove the effectiveness of their products (Peake, Kerr, & Sullivan, 2018). It has been argued that no single parameter is likely to capture the complexity of an athlete's training load and practitioners can be overwhelmed by the amount of data they receive from wearable sensors (Weaving, Jones, Till, Abt, & Beggs, 2017). Other limitations include the presence of ferromagnetic objects which can distort measurements from IMUs, the variability in

precise positioning which can affect data accuracy, and loss of data during wireless transfer due to interference from mobile phones or other devices that are on the same transmission frequency (Alonge, Cucco, D'Ippolito, & Pulizzotto, 2014; Blair, Duthie, Robertson, Hopkins, & Ball, 2018; Papi, Spulber, Kotti, Georgiou, & McGregor, 2015; Reenalda, Maartens, Homan, & Buurke, 2016).

1.7 Summary of Previous VERT Validation Studies

To our knowledge, there currently exist a total of nine unique studies evaluating the VERT's measures of jump height and jump count (Borges et al., 2017; Brooks et al., 2018; Charlton et al., 2017; MacDonald et al., 2017; Mahmoud et al., 2015; Manor et al., 2018; McDonald, 2017; C. Skazalski et al., 2018; Staiger & Wahl, 2018). Collectively, these studies examined the validity and reliability of the VERT device for the aforementioned measures. The subjects recruited consisted primarily of elite volleyball players, but also included children, college students, active adults, and nonathletic older adults. The reference standards used for assessing the VERT's jump height measure were the Vertec (or a similar jump-and-reach apparatus), force platform, jump mat, laboratory motion analysis, and video analysis. The reference standard used for assessing the VERT's jump count measure was retrospective video analysis from practices and matches, in the studies that also focused on jump count.

Overall, eight out of nine of these studies conclude that the VERT device has acceptable validity and reliability for its measures of jump height and jump count (Borges et al., 2017; Brooks et al., 2018; Charlton et al., 2017; MacDonald et al., 2017; Mahmoud et al., 2015; Manor et al., 2018; C. Skazalski et al., 2018; Staiger & Wahl, 2018). One of these eight studies found that the VERT underestimates maximal and submaximal jump height (MacDonald et al., 2017). The VERT also may not be suitable for recording low jump heights or for measuring maximal jumping ability when precision is needed (Mahmoud et al., 2015; Manor et al., 2018; C. Skazalski et al., 2018). When deciding whether to use a device like the VERT, all of this should be taken into

consideration by practitioners, as well as the acceptable level of potential error for their population and testing objectives. Interestingly, one out of nine of these studies came to a very different conclusion. The results of this study showed that the jump heights between the VERT and a jump mat were consistently 10 cm apart, a magnitude of difference which could make the difference between blocking and missing the ball in a volleyball match (McDonald, 2017). The author concluded that the VERT's jump height measure is reliable but not valid, and therefore not recommended for practical use (McDonald, 2017).

In all the studies conducted to date, the VERT's measure of landing impact has not been investigated. This study was the first to our knowledge to conduct an external validation of VERT for the landing impact parameter.

1.8 Center of Mass During Jumping

The center of mass of the human body is a hypothetical point at which the combined mass of the body appears to be concentrated (Hall, 2018). In other words, this point can be described as the location at which the sum of torques produced by the weights of the body segments equals zero (Hall, 2018). A common method for determining the whole body center of mass is the segment method, which involves taking into account both the position and magnitude of the center of mass for each segment (e.g. thigh, shank, foot, upper and lower arms). A weighted average of all body segments added up together in space is then calculated. While the center of mass lies approximately anterior to the second sacral vertebra in the anatomical position, human beings do not remain fixed in this position and therefore the precise location of the center of mass frequently reconfigures with every new position of the body and limbs (Catena, Chen, & Chou, 2017). It is an elusive point that need not lie within the physical bounds of a person.

While the developers of the VERT claim that the device is positioned at the center of mass, this is assuming that the athlete is standing stationary in the anatomical position. During a spike jump

however, it is very likely that the center of mass will change dramatically. It is also worth reflecting on how the VERT-identified landing impact values apply to the true ground reaction forces experienced at the knee in volleyball. We argue that there may be little correlation between these values for several reasons. The first and perhaps most obvious reason is that the VERT is not positioned at the knee, but rather at the waist. The ground reaction force experienced at the waist will undoubtedly be lower than the knee because of the way force dissipates as it travels up the kinetic chain. The second reason is that the VERT-identified landing impact values are based on resultant accelerations, which provide an indirect estimate of ground reaction forces. The third reason is that the VERT assumes the center of mass remains the same as when an athlete is in the anatomical position. Consequently, the VERT would not be capturing potentially injurious forces at the knee, which occur when the center of mass is located behind the knee as in the single-leg decline squat clinical test for patellar tendinopathy.

1.9 The Acute:Chronic Workload Ratio

The ACR, first developed by Australian sport scientist Tim Gabbett and colleagues, has been discussed as a variable that may provide a snapshot of an athlete's loading history, which could potentially be used to gauge injury risk. The preliminary studies on ACR were focused on cricket and rugby athletes, and introduced the variable as the previous week's amount of work compared to the previous four week's average amount (Figure 1.9) (Gabbett, 2016; Hulin et al., 2014; Hulin, Gabbett, Lawson, Caputi, & Sampson, 2016). In these studies, both external load data (number of balls bowled for cricket, distance covered in meters for rugby) and internal load data (sRPE) were used to calculate ACR. Initially, it was suggested that the ideal value for ACR should be within the range of 0.8-1.3 as this was associated with the lowest risk of injury (Gabbett, 2016). An ACR that is above or below this range resulted in a 2-4 times higher injury risk (Figure 1.10) (Gabbett, 2016). Given this relationship between ACR and the likelihood of subsequent injury, it was suggested that the risk of injury could be reduced by preventing any spikes in the acute load by ensuring there is no more than a 10% increase from week to week

(Gabbett, 2016). At the same time, maintaining a high chronic load is necessary to develop fitness over time and keep the tissues ready for intense activity (Gabbett, 2016).

Sample data:
Week 1 = 1400
Week 2 = 1200
Week 3 = 1800
Week 4 = 1600
Week 5 = current week (no data available)

$$\frac{\text{ACUTE (fatigue)}}{\text{CHRONIC (fitness)}} = \frac{1600}{(1600+1800+1200+1400)/4} = 1.1$$

Figure 1.9 Example ACR calculation.

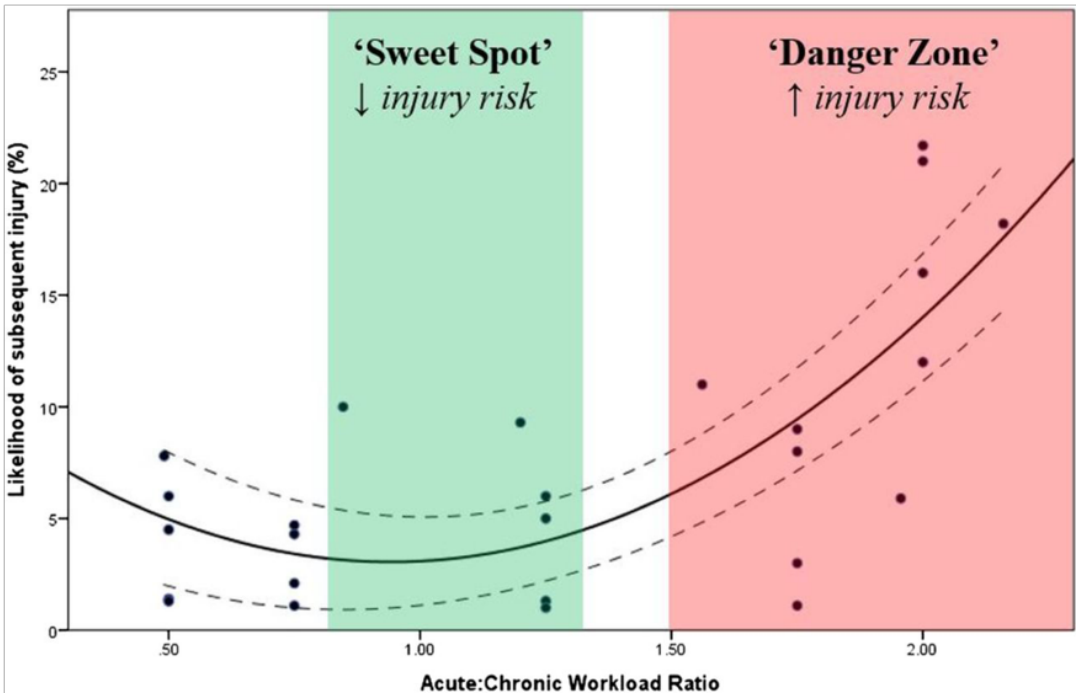

Figure 1.10 The relationship between acute:chronic workload ratio and likelihood of subsequent injury (%) (Gabbett, 2016, reproduced with permission).

More recently, the application of ACR to various other sports including soccer, football, basketball, and volleyball has been considered. Findings reveal that injury incidence is in fact associated with spikes in the ACR in these sports as well, with a combination of external and internal workload data appearing to have the most predictive power (Carey et al., 2017; Delecroix, McCall, Dawson, Berthoin, & Dupont, 2018; Timoteo et al., 2018; Weiss, Allen, McGuigan, & Whatman, 2017). When differing acute and chronic time windows were implemented to determine which best explains injury likelihood, it was found that a 3:21 days ratio performed better than the commonly used 7:28 days ratio for Australian footballers, suggesting that the best ratio to use might depend on the specific sport (Carey et al., 2017). Furthermore, the method for calculating ACR has been hotly contested. Traditionally, a rolling average (RA) method has been used as seen in Figure 1.9, but this model has received criticism as it does not account for the diminishing effects of training over time (Murray, Gabbett, Townshend, & Blanch, 2017). An exponentially weighted moving average (EWMA) is favoured by some, which weighs more recent workloads more heavily than older workloads (Murray et al., 2017; Williams, West, Cross, & Stokes, 2017). Finally, due to the inherent nature of the ACR, where the acute load is always a component of the chronic load (Figure 1.11), it has been demonstrated that these two variables will be mathematically coupled (Windt & Gabbett, 2018). This results in a spurious correlation which may lead to biased inferences (Windt & Gabbett, 2018). Therefore, it has been suggested that uncoupled ACRs, where the acute load is completely independent of the chronic load, may help to overcome this problem (Figure 1.12) (Windt & Gabbett, 2018). At this stage, neither is shown to be superior to the other and researchers are encouraged to comprehend and outline how they are calculating the ACR, whether coupled or uncoupled (Windt & Gabbett, 2018).

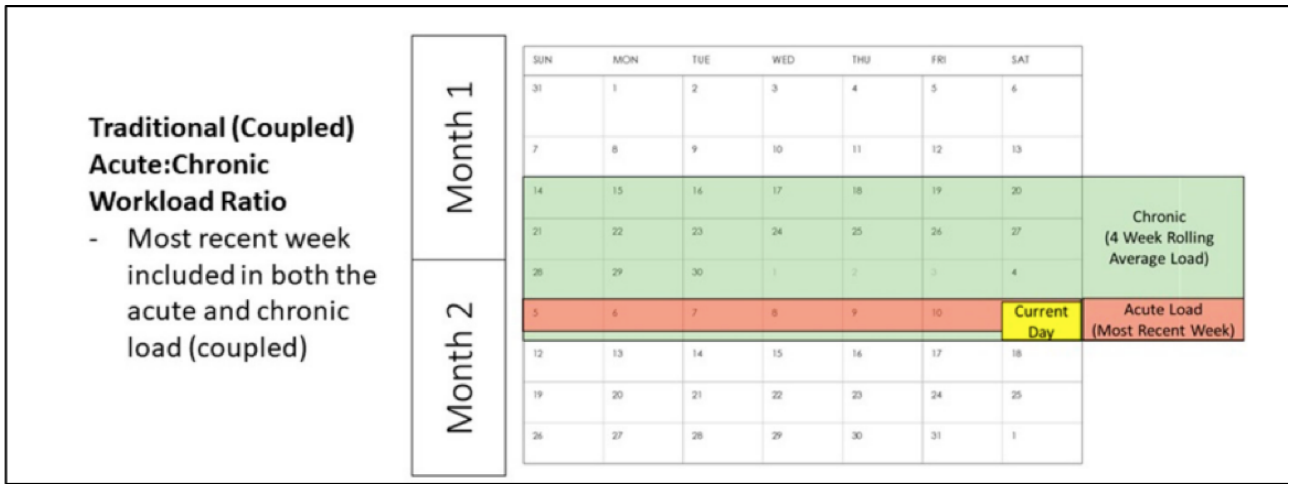

Figure 1.11 Traditional 'coupled' estimate of the acute:chronic workload ratio (Windt & Gabbett, 2018, reproduced with permission).

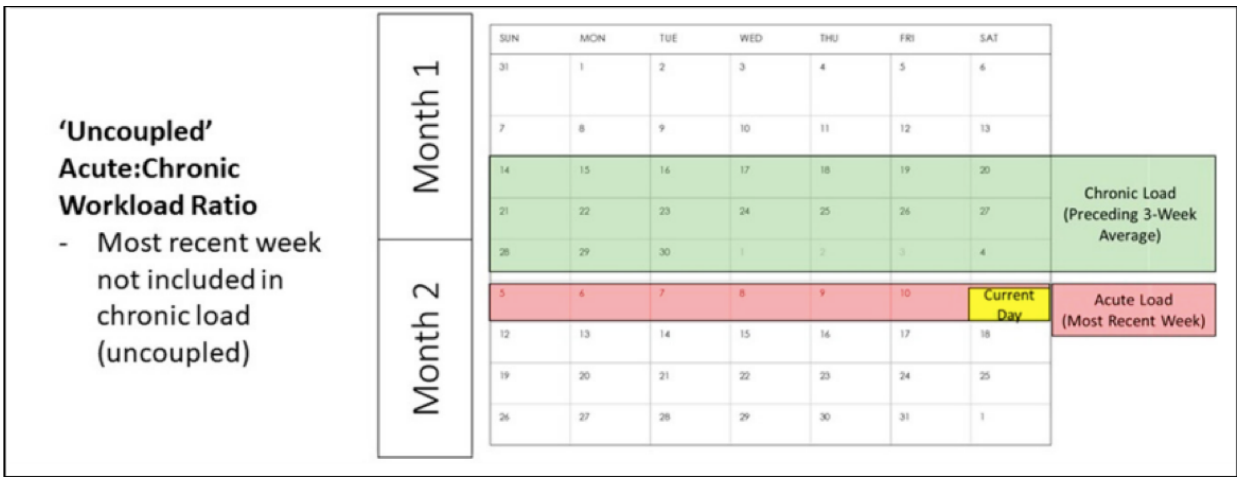

Figure 1.12 'Uncoupled' estimate of the acute:chronic workload ratio (Windt & Gabbett, 2018, reproduced with permission).

As previously mentioned, VERT data from a male varsity volleyball team was used in this study for a pilot examination of player data. In this data set, ACR was calculated by taking the average jump count per session in the last week (acute) divided by the average jump count per session in the last four weeks (chronic). It is important to recognize that this is in agreement with most

studies in terms of the 7:28 day ratio, and that it is based on coupled, RA estimates. To further analyze how the relationship between ACR and injury is influenced by methodological choices, four additional ACR variants were incorporated into the data set. The variants include 7:28/uncoupled/RA, 7:28/coupled/EWMA, 7:21/coupled/RA, and 3:21/coupled/RA estimates. Although there are no known studies that have used jump count to calculate ACR, it was used in this situation because jump count is closely related to our primary injury in question, jumper's knee, as compared to other variables such as sRPE. It should also be noted that despite the evidence supporting the use of ACR, it is simply one piece of a complicated puzzle and the limitations should be taken into consideration (C. Wang, Vargas, Stokes, Steele, & Shrier, 2020). This includes the fact that ACR does not account for intrinsic risk factors that can predispose an athlete to injury such as age, sex, previous injury, biomechanics, and cardiovascular fitness. More research is needed to understand how ACR can be used optimally.

1.10 Objective and Aims

The objective of this research study was to explore the potential utility of the VERT system as a load monitoring tool in elite volleyball players. This research project had the following specific aims:

1. To examine the accuracy of VERT landing impact values in university volleyball players
2. To conduct an exploratory analysis of player data over the course of a university volleyball season, documenting player compliance, completeness and integrity of the data set, and documenting whether established relationships between load characteristics (sRPE, ACR, average jump height, jump count, time in season, player position) and knee pain scores are observed in this data set.

1.11 Hypotheses

Based on the literature and specific aims for this research study, the following hypotheses were formed:

1. We anticipate that the absolute VERT landing impact values will fall within 10% of the landing impact values derived from a research-grade accelerometer, known as the Shimmer3 inertial measurement unit.
2. We expect to see agreement with the literature in that sRPE, ACR, average jump height, and jump count are positively associated with knee pain. We expect knee pain to increase over the course of the season and for leftsides/middle blockers to report the highest pain scores.

1.12 Significance of Research

If found to be accurate, the VERT system may offer a solution for high performance teams – athletes, coaching staff, and medical staff - to assess jump load via an inexpensive, simple and efficient method. Safe workload prescriptions may be determined and monitored using the VERT system, in turn maximizing performance and minimizing injury. As well, the results of the pilot examination of player data will contribute to developing a better understanding of patellar tendinopathy and its risk factors, allowing clinicians to provide more evidence-based advice to patients on how to self-manage their condition in order to remain physically active while promoting recovery.

Chapter 2: Methods

2.1 VERT Validation

2.1.1 Participant Information

The study population included 14 varsity volleyball players, with 11 players recruited from the UBC Men's Volleyball Team and 3 players recruited from the UBC Women's Volleyball Team. The head coaches were asked to give out study cards to their athletes to gauge interest (Appendix A). All participants were offered a $10 JJ Bean gift card at the end of their study visit for participating. Those with a background of any severe injury affecting the lower extremity in the past twelve months, including any orthopedic injuries with significant structural damage (e.g. ACL tears, fractures, chondral injuries) or requiring surgery, were asked for their specific diagnosis. This did not make one ineligible unless they were told by a doctor or other health professional to avoid all jumping activities. The same criterion applied if subjects presented with articular or muscle pain in the legs, or had a diagnosis of patellar tendinopathy. Ethical approval from the Clinical Research Ethics Board at the University of British Columbia was obtained (Study Number: H19-00163).

2.1.2 Study Design

Research-grade accelerometers from the Motion Analysis and Biofeedback Lab at UBC were used as the comparator for the VERT, and also worn at the waist in an adjustable belt. The research-grade accelerometer, known as the Shimmer3 Inertial Measurement Unit (Shimmer), was set to the highest sampling frequency possible of 2048 Hz to ensure highest possible accuracy (Figure 2.1). Each participant performed a total of 10 countermovement jumps (CMJs)

while wearing both the VERT and Shimmer devices (Appendix B). The first block consisted of 5 maximal CMJs. The second block consisted of 5 submaximal CMJs at 80% of maximum height achieved in the first block. The rest periods were 20 seconds between trials of the same block and 2 minutes between blocks, to avoid the effects of fatigue and allow for clear data visualization. Data collection occurred both during and outside of the scheduled varsity volleyball practices in War Memorial Gym (WG), based on player availability. Varsity athletes engaged in a practice session and participating in the study were permitted to step aside from the practice for testing purposes. Coaches and training staff were available to provide additional support as needed.

Figure 2.1 Shimmer3 inertial measurement unit.

2.1.3 Shimmer Calibration and Configuration

Prior to commencing the protocol, the Shimmer sensor wide range accelerometer was calibrated using the Shimmer 9DOF Calibration software. Next, using the ConsensysPRO software, the Shimmer was programmed with the appropriate firmware and configured such that the

undock/dock option was selected for the logging method, the wide range accelerometer data output was selected, set to the appropriate range of +/- 16g, and the sampling frequency was manually set to 2048 Hz. Although the VERT's sampling rate was unknown, we had good reason to believe that this sampling rate was significantly higher than the VERT. Many other studies with similar methodology have ensured equal sampling rates in devices being used. Our rationale for deviating from this approach was to allow us to examine the possibility that the VERT may be underestimating landing impact values, which would occur if sampling frequency is too low to capture the peak values.

2.1.4 Protocol

Participants, upon arrival for their study visit, were asked to provide informed consent and fill out two questionnaires. Firstly, we designed our own questionnaire to collect demographic data and determine if inclusion and exclusion criteria were satisfied (Appendix C). Secondly, participants were requested to fill out a modified version of the Oslo Sport Trauma Research Centre-Patellar Tendinopathy (OSTRC-P) questionnaire (Appendix D). The OSTRC-P questionnaire has been shown to be valid for self-reporting patellar tendinopathy and grading its severity in youth basketball (Owoeye, Wiley, Walker, Palacios-Derflingher, & Emery, 2018). Furthermore, it has been suggested to be an acceptable alternative to clinical evaluation in this particular setting (Owoeye et al., 2018). While we included a question about diagnosis of tendinopathy in our own questionnaire, the OSTRC-P questionnaire served as a more robust tool to identify if participants were likely to truly have the condition at the time of testing. However, a definitive diagnosis could not be extrapolated from this questionnaire as further validation is warranted in volleyball and it lacks the ability to rule out knee conditions which may coexist with patellar tendinopathy.

Once consent and questionnaires were completed, body mass and height measurements were recorded with a portable weigh scale (Weight Watchers 14C, Conair Consumer Products, Woodbridge, Ontario) and standing height measure (HM200P, Charder Medical, Taichung, Taiwan). Participants were given the option to warm-up on a stationary bike (M3, Keiser, Fresno, California) at a self-selected, comfortable pace. As some participants were arriving for their study visit directly from a practice session, they had already warmed up. At this time the Vertec (5013, Jump USA, Sunnyvale, California), a common apparatus for measuring vertical jump ability, was set up to allow enough room for jumping and landing in a safe position without hitting any objects. The experimenter provided a description of the procedure and this also included a physical demonstration for the participants. Participants were offered the opportunity to execute 2-3 practice CMJs. The exact instructions for the CMJ were to start from an upright standing position underneath the Vertec vanes, squat downward, immediately jump vertically off the ground, reach up with both arms, move as many vanes as possible, and make sure to land in the same starting position. Additionally, it was imperative to minimize movement between the jumps and blocks, in order to isolate the jumps in the resulting data and reduce unnecessary noise that could lead to misinterpretation.

Standing reach height was measured by instructing participants to reach as high as possible with both hands while pushing as many vanes on the Vertec as possible. This was measured once and it was essential for the heels to remain on the ground to yield an accurate standing reach. Participants were instructed to position the VERT on the anterior aspect of the waist with the device held securely in the commercially available VERT elastic waistband. The VERT therefore remained in the same position and orientation intended by the developers. Participants were told to position the Shimmer adjustable belt directly on top and maneuvered the bands such that the two devices were on the anterior aspect of the waist, adjacent to each other, and on either side of the navel with sufficient spacing to prevent making contact with each other. With the participant standing still in the start position underneath the Vertec, the Shimmer was undocked from the docking station and set on a flat surface to log dead air for 2 minutes. Simultaneously, the VERT data collection was started via the iPad application. The Shimmer was carried over to the participant and clipped into the Shimmer adjustable belt. Participants were asked to perform

5 maximal CMJs with 20 second rest intervals. During the rest intervals, both the highest magnitude impact and VERT-identified landing impact values were recorded for the most recent jump, as displayed on the VERT iPad application.

When finished the jumps from the first block, a rest period of 2 minutes was granted. It was critical that participants refrained from walking around or jumping during this rest period in order to isolate the jumps in the resulting data and reduce unnecessary noise that could lead to misinterpretation. Maximum jump height was obtained by subtracting the standing reach height from the highest vane displaced in the first block. The result was multiplied by 0.80 to yield submaximal jump height. The Vertec was adjusted such that the vane corresponding to submaximal jump height served as a singular target.

Participants began the second block of 5 submaximal CMJs with 20 second rest intervals. During the rest intervals, both the highest magnitude impact and VERT-identified landing impact values were recorded for the most recent jump, as displayed on the VERT iPad application. When finished all jumps, participants were advised to stand motionless for another 20 seconds. The Shimmer was removed to log dead air for 2 minutes while the participant continued to stand still. The Shimmer was docked and the VERT data collection was stopped concurrently via the iPad application.

Shimmer data was imported to the ConsensysPRO software, and subsequently exported as an excel file onto a USB flash drive. VERT data was downloaded as an excel file from the myVERT online server found at vts.myvert.com.

2.1.5 VERT and Shimmer Data Processing

Following the study visits, further data processing was necessary in order to align the jump data of interest from both the VERT and Shimmer devices. For the purposes of explaining the steps that were taken to achieve this alignment, sample data from a pilot session will be used.

As seen in Figure 2.2, a screenshot from the VERT iPad application, a series of 6 jumps has been registered by the device and this is evident in the *Jumps Vs. Time* graph. The *Impacts Vs. Time graph* allows visualization of the resultant accelerations upon the landings for each of those jumps. This is indicated by the yellow bars and we refer to this as the VERT-identified landing impact values. In the same graph, we also see the resultant accelerations purported by the manufacturer to be from movements other than landing impact. This is indicated by the red bars. During the experiment, it was noted that VERT-identified landing impacts sometimes appeared to be incorrectly flagged as red bars, and therefore we recorded both the VERT-identified landing impact and the highest magnitude impact values for each jump. The VERT excel file downloaded from the myVERT online server shows the same impact data with a higher degree of precision and time-stamped (Figure 2.3). The exact values were located in the Excel file and used to replace the imprecise numbers initially documented. For example, in Figure 2.2 we see that around 3:12:46 the subject achieved 9.5 Gs, and in Figure 2.3 the true value of 9.515251 Gs can be identified.

Unlike the VERT, the Shimmer does not offer data in a real-time and user-friendly format. Only the raw acceleration values for each of the X-Y-Z axes are given in m/s^2. The resultant accelerations must be calculated from the separate components using the formula:

Resultant acceleration = √[(acceleration in X)^2 + (acceleration in Y)^2 + (acceleration in Z)^2]

It is important to remember to convert the units of the resultant acceleration from m/s^2 to Gs by using the conversion 1G = 9.81m/s^2. The Shimmer excel file, after being exported from the ConsensysPRO software and containing these calculations, can be seen in Figure 2.4. Scatter

plots were generated using the time stamp and resultant acceleration in Gs columns with spikes corresponding to jumps clearly visible (Figure 2.5). The maximum values of each spike, or the resultant accelerations upon landings, could then be directly compared to similar values from the VERT.

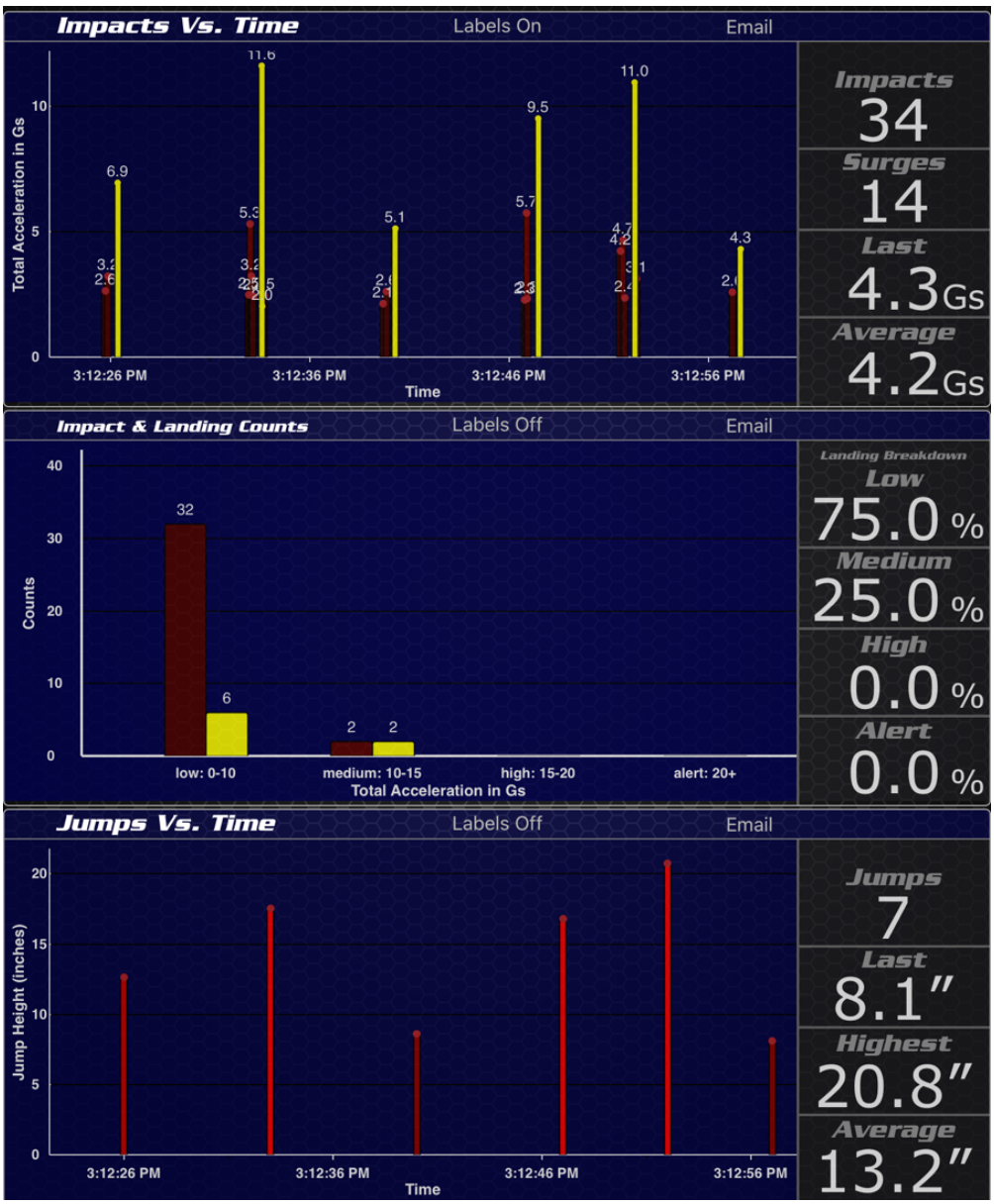

Figure 2.2 Screenshot from VERT iPad application.

	A	B	C	D
1	Date	Time		Peak Gs
2	11/14/2019	3:12:26	PM	2.638181
3	11/14/2019	3:12:26	PM	3.234192
4	11/14/2019	3:12:26	PM	6.946222
5	11/14/2019	3:12:33	PM	2.473863
6	11/14/2019	3:12:33	PM	5.315073
7	11/14/2019	3:12:33	PM	3.234192
8	11/14/2019	3:12:33	PM	2.428992
9	11/14/2019	3:12:33	PM	11.621101
10	11/14/2019	3:12:33	PM	2.012461
11	11/14/2019	3:12:34	PM	2.453569
12	11/14/2019	3:12:40	PM	2.12132
13	11/14/2019	3:12:40	PM	2.624881
14	11/14/2019	3:12:40	PM	5.132251
15	11/14/2019	3:12:47	PM	2.282542
16	11/14/2019	3:12:47	PM	5.735852
17	11/14/2019	3:12:47	PM	2.328089
18	11/14/2019	3:12:47	PM	9.515251
19	11/14/2019	3:12:51	PM	4.230839
20	11/14/2019	3:12:52	PM	4.674398
21	11/14/2019	3:12:52	PM	2.362202
22	11/14/2019	3:12:52	PM	10.956734
23	11/14/2019	3:12:52	PM	3.116087
24	11/14/2019	3:12:57	PM	2.596151
25	11/14/2019	3:12:57	PM	4.31509

Figure 2.3 VERT excel data.

	A	B	C	D	E	F
1	Shimmer_B5	Shimmer_B5	Shimmer_B5	Shimmer_B5	accel_result	accel_result_G
2	ms	m/(s^2)	m/(s^2)	m/(s^2)	m/(s^2)	G
3	1.57E+12	9.18660287	3.90430622	-1.5311005	10.0985914	1.02941808
4	1.57E+12	8.80382775	3.90430622	-1.1483254	9.69895052	0.98867997
5	1.57E+12	8.80382775	3.90430622	-1.2248804	9.70831201	0.98963425
6	1.57E+12	9.03349282	3.90430622	-1.0717703	9.89930762	1.00910373
7	1.57E+12	8.88038278	3.75119617	-1.2248804	9.71766448	0.99058761
8	1.57E+12	8.80382775	3.98086124	-1.2248804	9.73935169	0.99279834
9	1.57E+12	8.6507177	3.90430622	-1.1483254	9.56018697	0.97453486
10	1.57E+12	8.57416268	3.90430622	-0.9186603	9.46592887	0.96492649
11	1.57E+12	8.57416268	3.90430622	-0.9952153	9.47366488	0.96571507
12	1.57E+12	8.88038278	3.8277512	-0.9952153	9.72128237	0.99095641
13	1.57E+12	8.80382775	3.8277512	-1.1483254	9.66838732	0.98556446
14	1.57E+12	8.57416268	3.8277512	-1.0717703	9.45074794	0.96337899
15	1.57E+12	8.57416268	3.67464115	-0.9952153	9.38134888	0.95630468
16	1.57E+12	8.6507177	3.75119617	-1.1483254	9.49868626	0.96826567
17	1.57E+12	8.72727273	3.90430622	-0.9952153	9.61245805	0.97986321
18	1.57E+12	8.57416268	2.60287081	-0.9186603	9.00750459	0.91819619
19	1.57E+12	8.72727273	3.8277512	-0.9952153	9.58161897	0.97671957
20	1.57E+12	8.72727273	3.8277512	-0.9186603	9.57397019	0.97593988
21	1.57E+12	8.57416268	3.8277512	-0.9186603	9.43461083	0.96173403
22	1.57E+12	8.42105263	3.8277512	-1.0717703	9.31206198	0.94924179
23	1.57E+12	8.6507177	3.8277512	-0.9186603	9.50423762	0.96883156
24	1.57E+12	8.34449761	4.05741627	-0.9952153	9.33186587	0.95126054
25	1.57E+12	8.49760766	3.8277512	-1.0717703	9.38134888	0.95630468
26	1.57E+12	8.72727273	3.8277512	-0.8421053	9.56692792	0.97522201
27	1.57E+12	8.49760766	3.90430622	-0.7655502	9.38291053	0.95646387

Figure 2.4 Shimmer excel data. Showing 27 of 478018 rows.

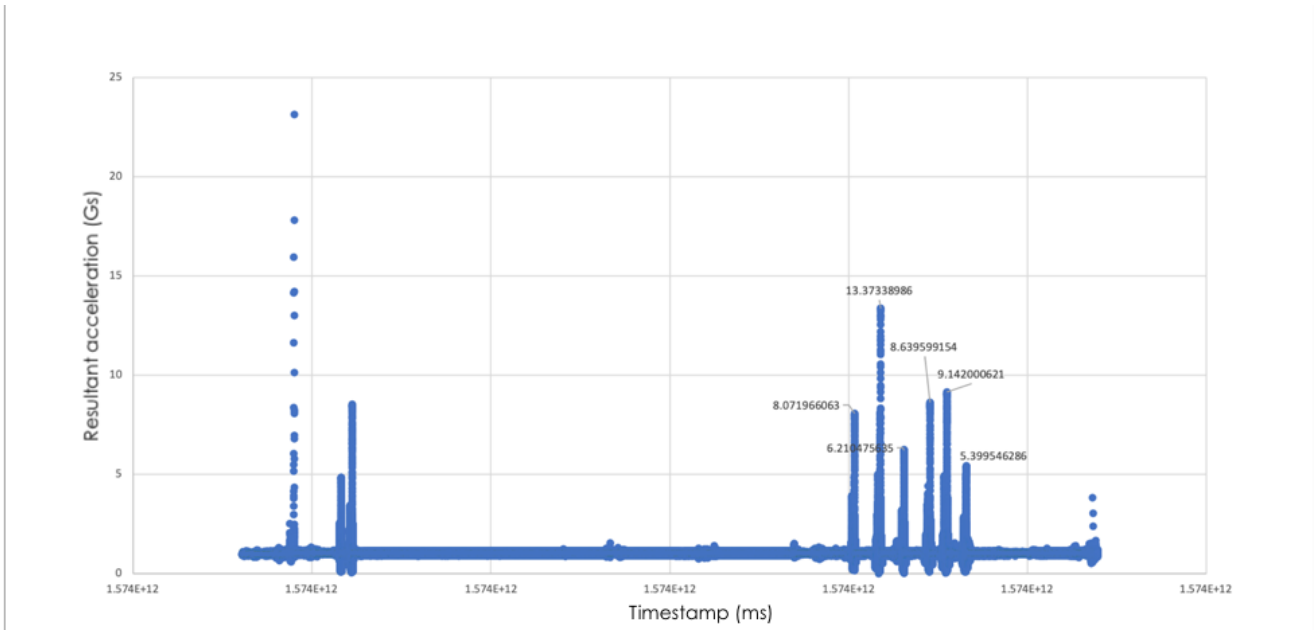

Figure 2.5 Shimmer scatter plot generated from Shimmer excel data in Figure 2.4. Please ignore the left hand side of this plot which is noise from logging dead air, carrying the Shimmer over to the participant, and clipping into the Shimmer adjustable belt.

2.1.6 Statistical Analysis

It was important to see how the measurements from VERT and measurements from our research-grade accelerometers correlate. Two versions of this analysis were performed, the main version that used the highest magnitude impact values and another supplementary version that used the VERT-identified landing impact values. For each pair of measurements from each of the devices, the percentage difference was calculated using Shimmer's peak landing impact value as the comparator. For example, if Shimmer measured 10 m/s^2 and VERT measured 7 m/s^2, then the percentage difference was -30%. The percentage differences were used to first generate a histogram to examine the distribution of differences. A Bland-Altmann plot approach was then used to assess the amount of discrepancy between the VERT and Shimmer across the range of G values, with adjustments made due to the presence of repeated measures (Bland & Altman, 1999,

2007). Due to the repeated measurements performed on the same individual, it was important to control for the dependency between measurements within an athlete. Thus, a one-way ANOVA was used to compute the necessary variance components to correctly estimate the variability of the differences. By doing this, it was possible to more accurately construct the limits of agreement and the confidence interval for the mean bias, both of which were created in the Bland-Altman plot approach. Intraclass correlation coefficients (ICC) and concordance correlation coefficients (CCC) were also calculated. CCC is a useful alternative to the ICC when there are repeated measures within measured subjects. There are many versions of CCC, and in this analysis we use the version which is computed from variance components of a linear mixed effect model for longitudinal repeated measures (Carrasco, King, & Chinchilli, 2009). We additionally assume a compound symmetric covariance structure. This calculation was conducted using the "ccclon" function from the "cccrm" package in R.

2.2 Pilot Examination of Player Data

2.2.1 Data Collection

The UBC Thunderbirds Men's Volleyball Team has implemented the VERT technology for load monitoring over the past 4 seasons. The volleyball season is typically about 30 weeks, commencing in late August and ending in March. This began with the original VERT in the 2016-17 season and was followed by the introduction of the newer G-VERT in 2017-18. All players on the team were required to wear it during every single practice and match throughout the season. After each session, players were asked to report their rating of perceived exertion (RPE) and pain scores for regions of common overuse injuries, both on a scale that runs from 0-10 (See Appendices E & F).

2.2.2 Data Structure

The data, organized in an excel spreadsheet (See Appendix G), was from volleyball players and longitudinal in nature collected over a 30 week period. Compliance was 100%. There was an ID variable which identified each player by their jersey number as well as a player position variable. We had a date variable, and for each date the type of training they did (i.e. practice or match), their average jump height, jump count, perceived exertion, session duration, pain scores for regions of common overuse injuries (shoulder, back, knee), and acute:chronic workload ratio.

2.2.3 Exploratory Analysis

The exploratory analysis focused on the 2016-17 data set. The approach was to first understand the data set and its contents, identifying what data were present and what data were missing. These were quantified with descriptive statistics. Following this step, the data set was cleaned and organized such that further analysis could be performed. This entailed removing certain variables such as the "libero" position (often did not wear the device as this position requires very little jumping), "other" training type (this made up a low proportion of entries and was unclassified), "shoulder" pain (not of interest), and "back" pain (not of interest). Data which were missing because of technical issues presented as zeroes (examples of typical technical issues included failed charging process of VERT devices, iPad lost connection or died, WiFi server down); these zeroes were removed as part of the data cleaning process. Next, the data was described by preparing summary statistics and looking for any trends/relationships that exist, especially those relating measures of load to knee pain. All analyses was done with R Statistical Software. More specifically, a four-step process was followed.

Step 1, Examining the Knee Pain Outcome

A bar plot was generated to explore the number of observations made in each knee pain rating, showing the distribution of knee pain over all weeks. Each rating 0 to 10 was on the X axis, and the number of measures was on the Y axis.

Step 2, Determining the Outcome

There were two potential outputs that could be used. Knee pain scores (ordinal scale from 0 to 10) were available for each session, and alternatively, player medical records confirming diagnosis of tendinopathy could have been requested for viewing. It was determined that knee pain score should be used as the outcome in the analysis. Tendinopathy is a slowly developing chronic condition, so giving it a binary "yes" or "no" depending on when the player went to the doctor is slightly arbitrary. Therefore no medical information was accessed.

We can be fairly confident in making the assumption that knee pain scores serve as an indicator of patellar tendinopathy or jumper's knee in the majority of players, because there were no other substantial knee injuries and simply due to the nature of this population, although it is possible that a subset of players experienced patellofemoral pain. In an epidemiological study probing for jumper's knee among athletes from different sports, the prevalence was highest in volleyball due to the high demands on the leg extensors (O. B. Lian, Engebretsen, & Bahr, 2005). We also know that competing at an elite level compared to a non-elite level and sex are significant risk factors for developing patellar tendinopathy, with men being more prone to the disorder (O. B. Lian et al., 2005; Zwerver et al., 2011). That being said, although it is reasonable to assume knee pain implies patellar tendinopathy, there is a chance that patellofemoral joint pain could be the issue and therefore this diagnosis cannot be ruled out entirely (Calmbach & Hutchens, 2003).

Step 3, Visualizations

Scatter plots were made for each week with pain rating on the Y axis and variables of interest on the X axis such as jump count. Bivariate plots were made to compare each variable to knee pain. Tables were also useful for each variable, containing summary statistics such as mean, minimum, maximum, etc., to get an idea of what sort of values they take. Box plots were made of knee pain score for each player to see the range of pain scores each player reported. This helped to see the amount of variation within and between players. Two more plots of interest included a scatter plot of pain score vs. time, and a scatter plot of jump count over time. These helped identify trends over the season. The distribution of knee pain per week was plotted as well.

Step 4, Modelling

A linear mixed effect model was used for several reasons. This model, unlike others such as multilevel modelling and time-to-event analysis, is well suited to this particular data set containing repeated measures, is less complex, allows us to see a relationship between knee pain and load variables, and does not throw out any data unlike others. A stepwise procedure was used to reduce the model complexity and remove unimportant variables using the Akaike Information Criterion (AIC). Coefficient estimates were produced, as well as estimates for each player's Z value or the random error specific to a player.

Furthermore, we conducted mixed effect modelling using each of the ACR variants as a predictor in its own model against knee pain score. The purpose of this was to compare the relationships between knee pain score and each of the ACR variants. Two versions of this analysis were performed, both without and with fixed additional covariates. The advantage of the first approach (only modelling with ACR variants) was that the direct relationships between ACR and knee pain score could be observed, but the disadvantage was that we did not adjust for the effect of other covariates of interest. The second approach (modelling with ACR variants and

fixed additional covariates), overcame these limitations such that comparisons between the effects of different ACR variants were made after the adjustment. The following variables were included as the set of covariates: (1) position, (2) jump count, (3) average jump height, and (4) date.

Chapter 3: Results

3.1 VERT Validation

3.1.1 Participant Demographics

The demographics for the 14 participants can be found in Table 3.1.

Variable	All Subjects (n=14)
Age (yr), mean ± SD	20.9 ± 1.5
Male	11
Female	3
Height (cm), mean ± SD	187.6 ± 10.5
Standing reach (cm), mean ± SD	244.6 ± 15.2
Body mass (kg), mean ± SD	80.9 ± 10.8
Maximum jump height (cm), mean ± SD	59.2 ± 10.2

Table 3.1 VERT validation participant demographics. SD = standard deviation.

3.1.2 Comparison of highest magnitude accelerations between VERT and Shimmer

In this section, the analysis that used the highest magnitude impact values is detailed. We also conducted a supplementary analysis that used the VERT-identified landing impact values instead (Appendix W). The supplementary analysis showed that the correspondence between VERT-identified landing impact values and peak acceleration values from the Shimmer were even worse.

Summary statistics of the devices can be found in Table 3.2. We observe that the mean VERT value is lower than the Shimmer. The standard deviations are similar, as well as the maximal and minimal values for each device.

	Mean (G)	SD (G)	Max (G)	Min (G)
VERT	7.8	3.5	24.3	3.6
Shimmer	10.0	4.1	21.2	4.1

Table 3.2 Summary statistics of devices. SD = standard deviation.

The results of the analysis are shown in the histogram and Bland-Altman plot below (Figures 3.1 and 3.2). The histogram of percentage differences reveals a general tendency for VERT measurements to be considerably lower than the Shimmer measurements, with percentage differences mostly between -60% and 0%. There is sufficient enough variability in the measurements such that percentage differences are also fairly large in the positive direction, generally up to 50%. Overall we observe high variability from the initial histogram. Thus, the hypothesis that VERT measurements would fall within 10% of Shimmer measurements was rejected.

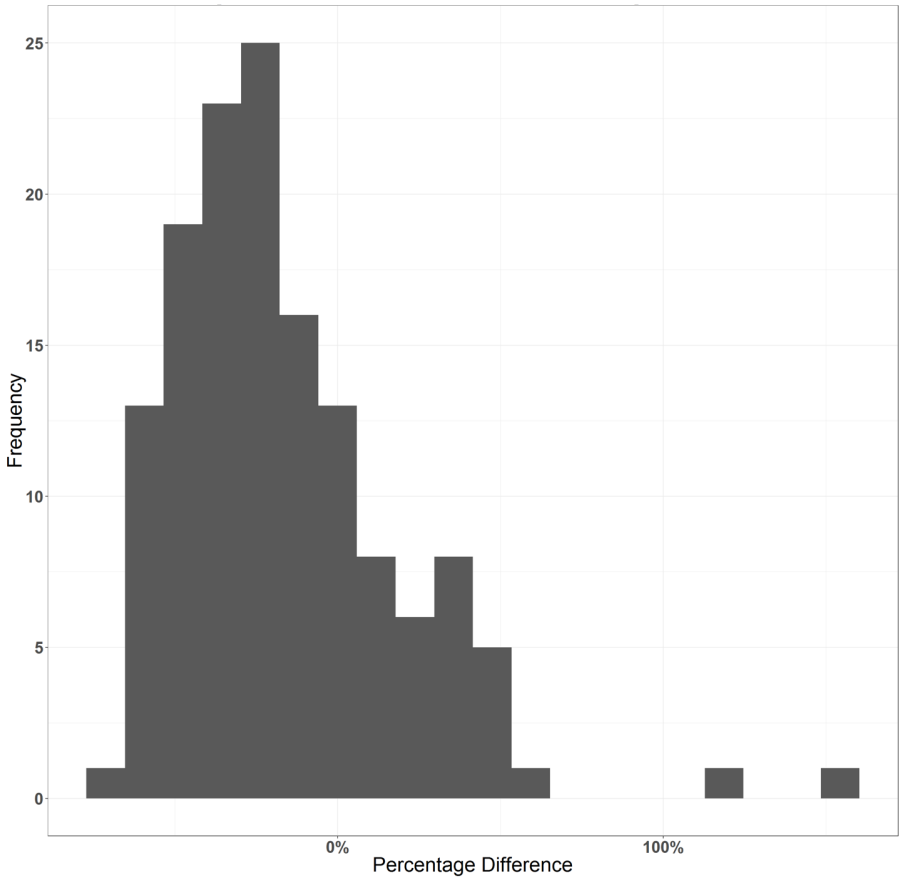

Figure 3.1 Histogram of VERT and Shimmer percentage differences.

There are two primary features to be examined in the Bland-Altman plot, the variability of differences (reflected by the limits of agreement and the distribution of points), and the mean bias. The limits of agreement within this plot are remarkably wide, with limits of -84.13% and 52.37%, suggesting that percentage differences between VERT and Shimmer vary by a large amount. This makes one question the validity of the VERT device when it comes to measuring landing impacts. Additionally, when examining the mean bias, we observe that its value is -15.88%. The confidence interval spans from -35.99% to 4.23%. As it overlaps with 0%, it suggests the mean bias may not be significantly different from 0%, but this is likely attributed to the high variability that we observe in the differences. With such a wide-ranging confidence interval, the mean bias may nevertheless be large and negative since the lower bound of the

confidence interval stretches down to -35.99%. There may be a tendency for VERT to have lower measurements than Shimmer, resulting in a bias.

In examining the distribution of points themselves, it is evident that when the mean between the pairs of measurements is less than 10, then the points are nearly evenly distributed around the mean bias. When the mean of a measurement pair exceeds 10, then a peculiar weak trend is seen where percentage differences are very low but increase towards the mean bias and beyond. This is indicative of lower reliability, and hence validity, of the VERT device at landing impacts on the higher end of the spectrum. Two very large outliers are observed for player 4, with the VERT device measuring more than double the Shimmer device. However, outside of those two exceptions, differences mostly remain within or near the limits of agreement.

With respect to the effect of player, there do not appear to be any notable relationships, although we do see clustering of points for some players such as for players 8 and 14, suggesting consistency in measurements for some players. In contrast, percentage differences for player 4 seem to be scattered all over. Additionally, with respect to the effect of jump type, there also is no clear relationship with percentage differences from the plot itself.

Overall this analysis reveals that the validity of the VERT device as a suitable alternative to Shimmer for the measurement of landing impact in volleyball players seems to be generally poor, with high limits of agreement indicative of high variability in percentage differences.

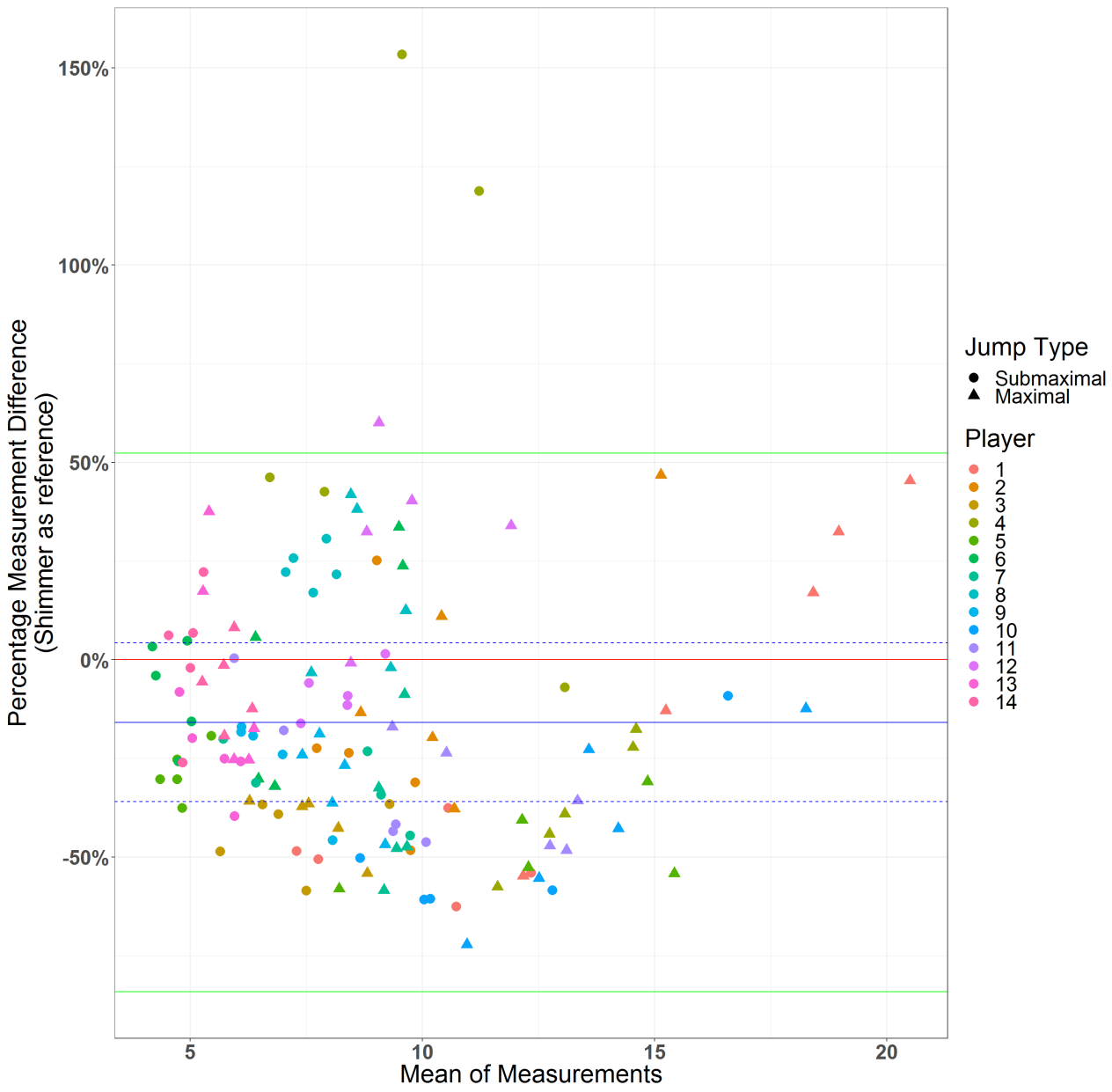

Figure 3.2 Bland-Altman plot for VERT and Shimmer agreement.

The calculated ICC is 0.4908, using the ICC for a two-way mixed effect model, single measures, and absolute agreement (McGraw & Wong, 1996). We are 95% confident that the ICC is between 0.3774 and 0.5896. The moderate size of the ICC value indicates some agreement between the two devices, but agreement is generally mediocre. Thus, the VERT device may not

be a valid substitute for the Shimmer device. The calculated CCC is 0.3678. We are 95% confident that the CCC is between 0.1153 and 0.5757. The mild size of the CCC value corroborates what we observe with the ICC value, although the measure of agreement is worse here once we account for the repeated measures within subjects.

3.2 Pilot Examination of Player Data

In the data set, the variables of date, week, player ID, player position, training type, and session duration had no missing values. Data was missing for jump count (7.3%), average jump height (26.3%), knee pain (18.7%), RPE (63.9%), sRPE (64.1%), and ACR (3.3%).

Preliminary visualizations and summary statistics generated for the exploratory analysis are included in Appendices H-S. The most pertinent aspects of the pilot examination of player data are the linear mixed effect model and comparison of ACR variants in separate mixed effect models, the results of which are detailed in this section.

3.2.1 Linear Mixed Effect Model

The formula for the model is shown below, using sum notation because of the large number of coefficients and terms. The assumptions of this model are that the player-specific random effects Z are identically and independently normally distributed, and that the observation-specific random errors E are identically and independently normally distributed. These assumptions also imply that the error terms should have constant variance. Diagnostic plots checking that the model meets the necessary assumptions stated above are included in Appendix T. sRPE was removed as a predictor due to the large number of missing values. For the other predictors, observations in which there was no missing data were used in this complete case analysis. We

are making the assumption that data is missing completely at random (MCAR) (Mack, Su, & Westreich, 2018), and thus the complete case analysis is unbiased.

Original formula: $\log(Y + 1) = \beta_0 + \sum_{k=T,J,H,A,P} \beta_k X_k + \sum_{j,k \text{ from } T,J,H,A,P} \beta_{jk} X_j X_k + Z + E$

β = Coefficients explaining the relationship between the predictors and knee pain score

Predictors:

X_T = Time (Days)

X_J = Jump count

X_H = Average jump height

X_A = ACR

$\vec{X}_P$ = Position (set up as a vector of indicators for each possible position)

Outcome:

Y = Knee pain score

Random Variables:

E = Random error specific to an observation

Z = Random error specific to a player

We observe that all the main effects of our predictors are kept after using the AIC for model selection, with 4 interaction terms kept (between ACR and jump count, between ACR and position, between average jump height and jump count, and lastly between date and position).

Formula after removing unimportant variables:

$\log(Y + 1) = \beta_0 + \sum_{k=T,J,H,A,P} \beta_k X_k + \beta_{J,A} X_J X_A + \vec{\beta}_{A,P} X_A \vec{X}_P + \beta_{J,H} X_J X_H + \vec{\beta}_{T,P} X_T \vec{X}_P + Z + E$

In the mixed effects model (Table 3.3), the leftside position is a reference category, meaning that all the values seen are simply comparisons to the reference value of leftside. The coefficient estimates and standard errors in Table 3.3 are exponentiated to improve interpretability, since the outcome of the model is log(knee pain score+1). Thus, with these exponentiated coefficients, we observe the corresponding percentage change in the knee pain score for every one unit increase in a predictor. For example, we see that if a player is in the opposite position, then that player will have an approximately 40% lower knee pain score than a player in the leftside position when holding all other variables constant (and assuming ACR=0 and Date=0). The percentage change is given directly by subtracting the exponentiated coefficient estimates by 1. Since we have interaction terms between some variables, they also need to be taken into account when determining the effect of a particular variable. For instance, if we want to examine the effect of the setter position on knee pain score when compared to the leftside position. If we assume ACR=1.5 and Date=0, for example, then we anticipate that a setter's knee pain score will be 105.9% higher than a leftside player (keeping all other variables constant), following the below equation:

$$\exp(\ln(0.985)*1 + \ln(1.635)*1.5 + \ln(0.997)*0) - 1 = 1.059$$

The numbers 0.985, 1.635 and 0.997 correspond to the exponentiated positionsetter coefficient, exponentiated ACR:positionsetter interaction coefficient and exponentiated date:positionsetter interaction coefficient, respectively. Note that since Date=0, the last term in the summation becomes 0. This logic of obtaining the percentage change in knee pain score can similarly be applied to any specific variable we wish to investigate more closely.

Many of these coefficient estimates are quite small however, suggesting that many of the predictors have a minor effect on knee pain score. The only statistically significant main effects ($p < 0.05$) are average jump height (2.7% decrease in knee pain score for every one unit increase, holding other variables constant) and date (-0.4%). For the statistically significant interactions, we observe the interaction between ACR and position setter (63% increase in knee pain score for

every one unit increase in ACR among setters when compared to leftside players), the interaction between average jump height and date (0.02%) and the interaction between date and position setter (-0.3%, with leftside position as baseline). The interaction between average jump height and jump count is not significant with a nearly negligible change. Now, even though the other predictors do not have significant coefficient estimates, this does not mean they do not contribute to the model. This simply indicates that we have insufficient evidence that the coefficient estimates are significantly different from 0 (or 1 for the exponentiated coefficients). The use of AIC to select variables (instead of statistical significance) ensures that we balance model goodness-of-fit and model complexity (to avoid overfitting). Although some predictors are not statistically significant, the model still offers insight into the effects of the predictors, albeit many of them (even if statistically significant) have only a minor effect on knee pain scores. The 95% confidence intervals reflect the precision of the coefficient estimates. For each confidence interval, we can be 95% confident that the true exponentiated coefficient estimate lies within the given interval. Some of these confidence intervals are quite wide (such as positionsetter and positionmiddle), indicative of great uncertainty regarding the effect of the given predictor. Some confidence intervals (such as for date and jump count) are narrow, meaning we have much greater precision and we have high confidence that the true value falls within a narrow range of values.

	Coefficient Estimate (Exponentiated)	Standard Error	95% Confidence Interval	p-value
(Intercept)	2.706	0.381	1.29-5.675	0.009
ACR	1.088	0.155	0.805-1.471	0.587
Average.Jump.Height	0.973	0.013	0.948-0.999	**0.041**
Jump.Count	1.004	0.003	0.999-1.009	0.100
Date	0.996	0.002	0.992-1.000	**0.032**
PositionMiddle	1.231	0.263	0.674-2.250	0.453
PositionOpposite	0.598	0.322	0.287-1.250	0.149
PositionSetter	0.985	0.324	0.470-2.065	0.963
ACR:Jump.Count	0.998	0.001	0.995-1.001	0.130
ACR:PositionMiddle	1.257	0.144	0.950-1.664	0.112
ACR:PositionOpposite	1.235	0.180	0.871-1.752	0.239
ACR:PositionSetter	1.635	0.190	1.130-2.365	**0.010**
Average.Jump.Height:Jump.Count	1.000	0.000	1.000-1.000	0.361
Average.Jump.Height:Date	1.000	0.000	1.000-1.000	**0.007**
Date:PositionMiddle	0.999	0.001	0.998-1.000	0.102
Date:PositionOpposite	1.001	0.001	1.000-1.003	0.075
Date:PositionSetter	0.997	0.001	0.996-0.999	**0.004**

Table 3.3 Linear mixed effect model summary.

Figures 3.3-3.5 provide some visualizations of the linear mixed effect model. In Figure 3.3, we see that the effects of jump count and ACR on knee pain are quite small compared to the effect of jump height, position, and of the progression of the season. Setters and middle blockers have the highest knee pain, and their scores seem to decline over the course of the season as seen by the negative slopes. The leftsides and opposites on the other hand, have a positive slope which means more knee pain as the season progresses.

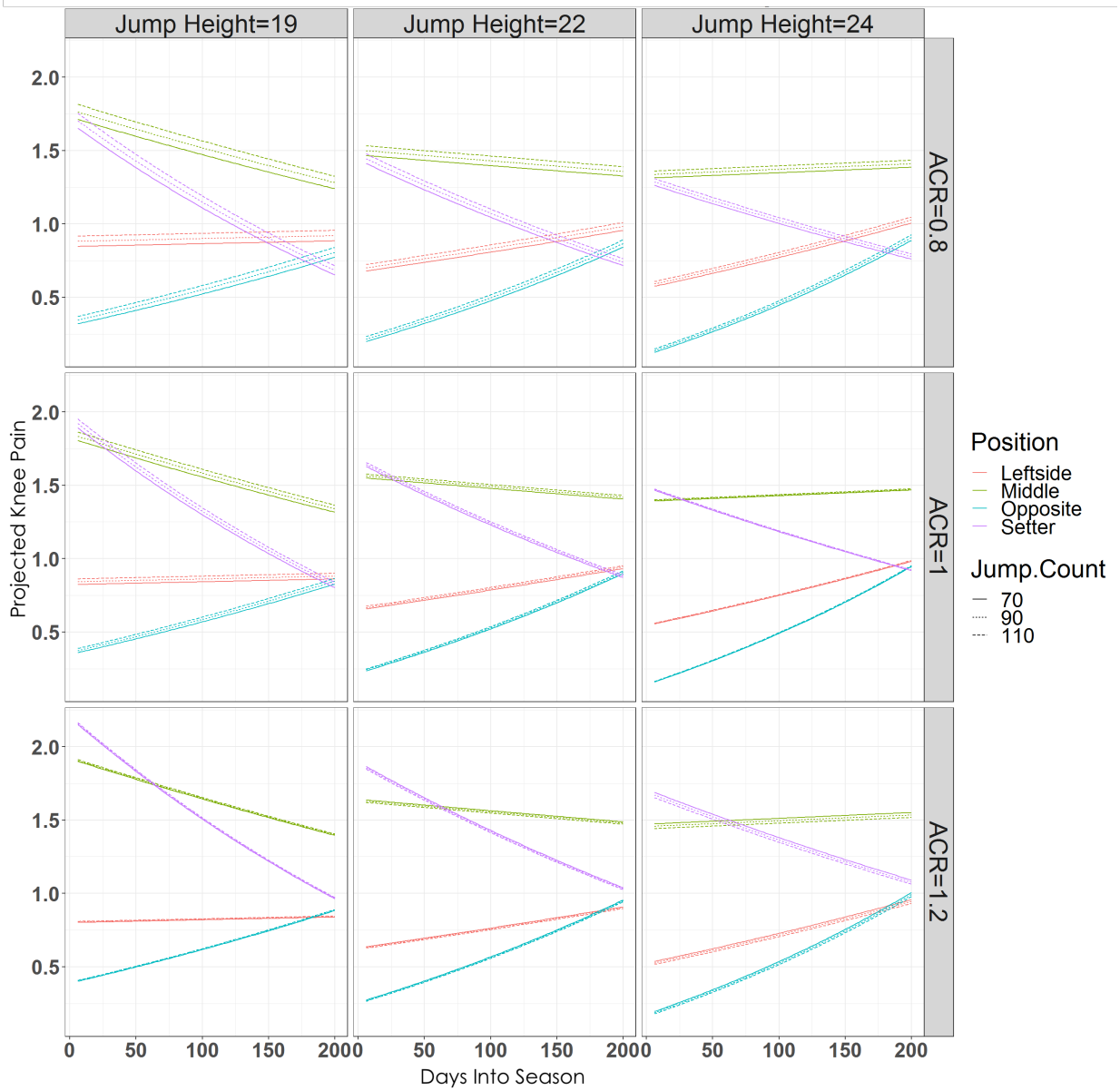

Figure 3.3 Linear mixed effect model predictions in various settings. Approximate 25%, 50%, 75% quantiles are used as values for ACR, jump height, and jump count. The ACR used in this plot is the original 7:28/coupled/RA estimate. Note that this plot does not capture how often different combinations actually appear in the data set, but rather simply shows what predictions would be in a host of different settings. Since average knee pain scores are much lower than the higher range reported, predictions higher than 2 are uncommon. Leftside (n=4), middle (n=4), opposite (n=2), setter (n=2).

In Figure 3.4, ACR, jump counts and jump height are fixed at roughly mean values, to show the general trend of knee pain scores over time for each position under the model. The plot observes the trends over time of knee pain in different positions, and in the background is included the lines of actual observed values in the data set (the lighter coloured lines represent the actual knee pain scores for each individual of that position).

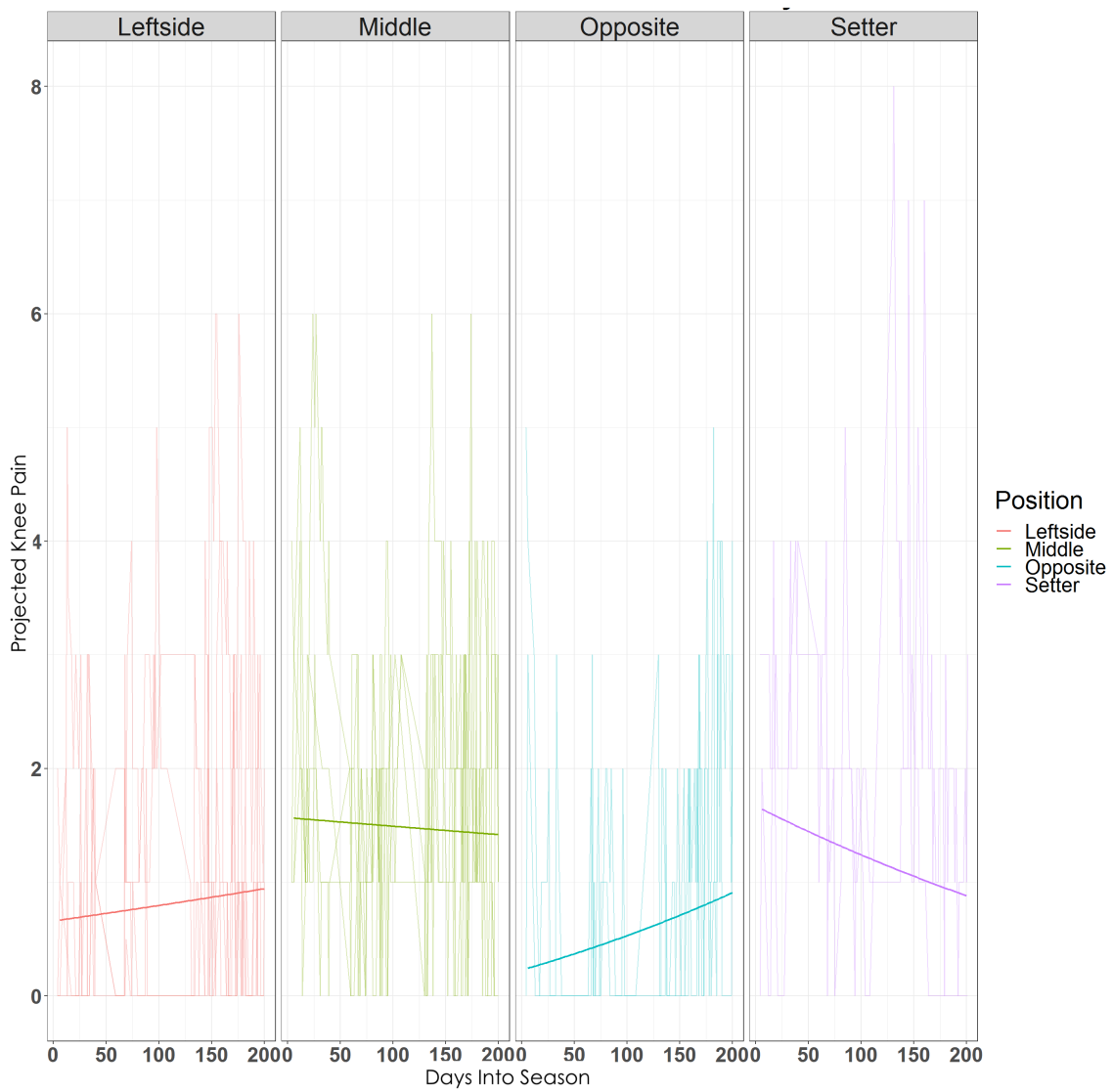

Figure 3.4 Projected knee pain at mean ACR (1), mean jump count (90), and mean jump height (22). The ACR used in this plot is the original 7:28/coupled/RA estimate.

In Figure 3.5, each player's knee pain score is plotted over time, overlaid with the statistical model's predictions of the player's knee pain trend. It is apparent that the model is very capable of picking up average trends over time, but often fails to capture abrupt fluctuations in knee pain.

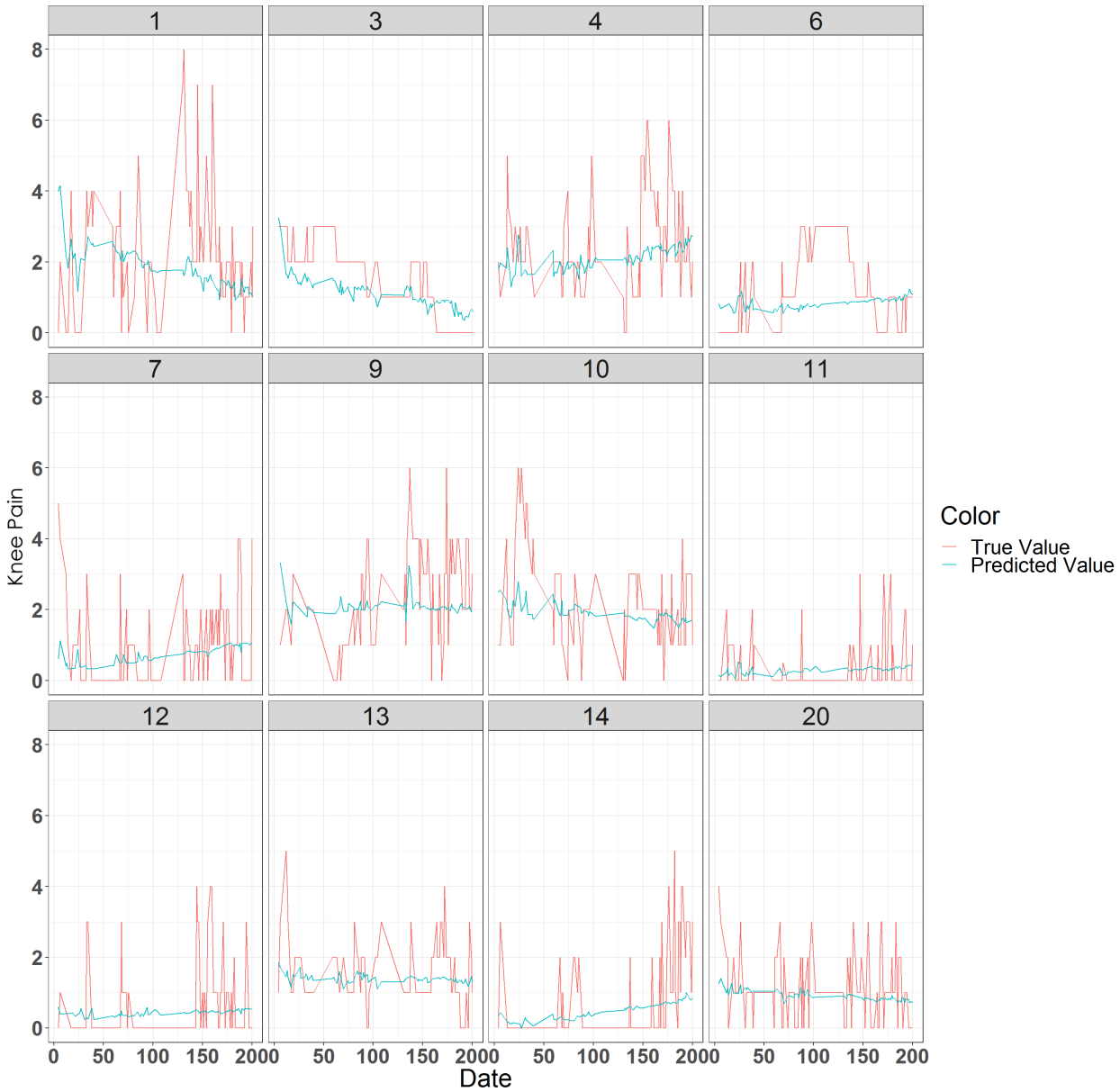

Figure 3.5 Players' predicted vs. observed trends.

One may rearrange the revised equation after AIC to calculate Y, and form a new estimate about a specific player's knee pain at certain values of all the predictors.

Population-level estimate of knee pain under certain settings:

If position is leftside: $Y = \exp(\beta_0 + \beta_A X_A + \beta_J X_J + \beta_H X_H + \beta_T X_T + \beta_{A,J} X_A X_J + \beta_{J,H} X_J X_H) - 1$

If position is not leftside: $Y = \exp(\beta_0 + \beta_A X_A + \beta_J X_J + \beta_H X_H + \beta_T X_T + \beta_P X_P + \beta_{A,J} X_A X_J + \beta_{J,H} X_J X_H + \beta_{A,P} X_A + \beta_{T,P} X_T) - 1$

Person-specific estimate of knee pain under certain settings:

If position is leftside: $Y = \exp(\beta_0 + \beta_A X_A + \beta_J X_J + \beta_H X_H + \beta_T X_T + \beta_{A,J} X_A X_J + \beta_{J,H} X_J X_H + Z) - 1$

If position is not leftside: $Y = \exp(\beta_0 + \beta_A X_A + \beta_J X_J + \beta_H X_H + \beta_T X_T + \beta_P X_P + \beta_{A,J} X_A X_J + \beta_{J,H} X_J X_H + \beta_{A,P} X_A + \beta_{T,P} X_T + Z) - 1$

3.2.2 Comparison of ACR Variants

We examined a total of 5 different ACR variants: (1) 7:28/coupled/RA, (2) 7:28/uncoupled/RA, (3) 7:21/coupled/RA, (4) 3:21/coupled/RA and (5) 7:28/coupled/EWMA.

To compute the last ACR variant, an equation was used to compute the acute EWMA and the chronic EWMA for each day (with EWMA of previous days influencing the EWMA of the current day), and from these two values we obtain the ACR as the acute EWMA divided by the

chronic EWMA (Murray et al., 2017; Williams et al., 2017). The corresponding equation can be found in the papers by Williams et al. (2017) and Murray et al. (2017), with N representing the number of days for the workload (7 for acute and 28 for chronic). Due to missingness in the data for jump count, the "yesterday's EWMA" was replaced with the last day in which a jump count was **not** missing in cases where yesterday's jump count was missing.

Figure 3.6 is a time series plot, demonstrating how the variant ACRs correspond to one another for each of the players. Overall, it appears that the variant ACRs are generally similar to one another, except for the 3:21/coupled/RA ACR measure which is lower than the other variant ACRs. This is intuitive considering it works with a 3-day sum instead of a 7-day sum.

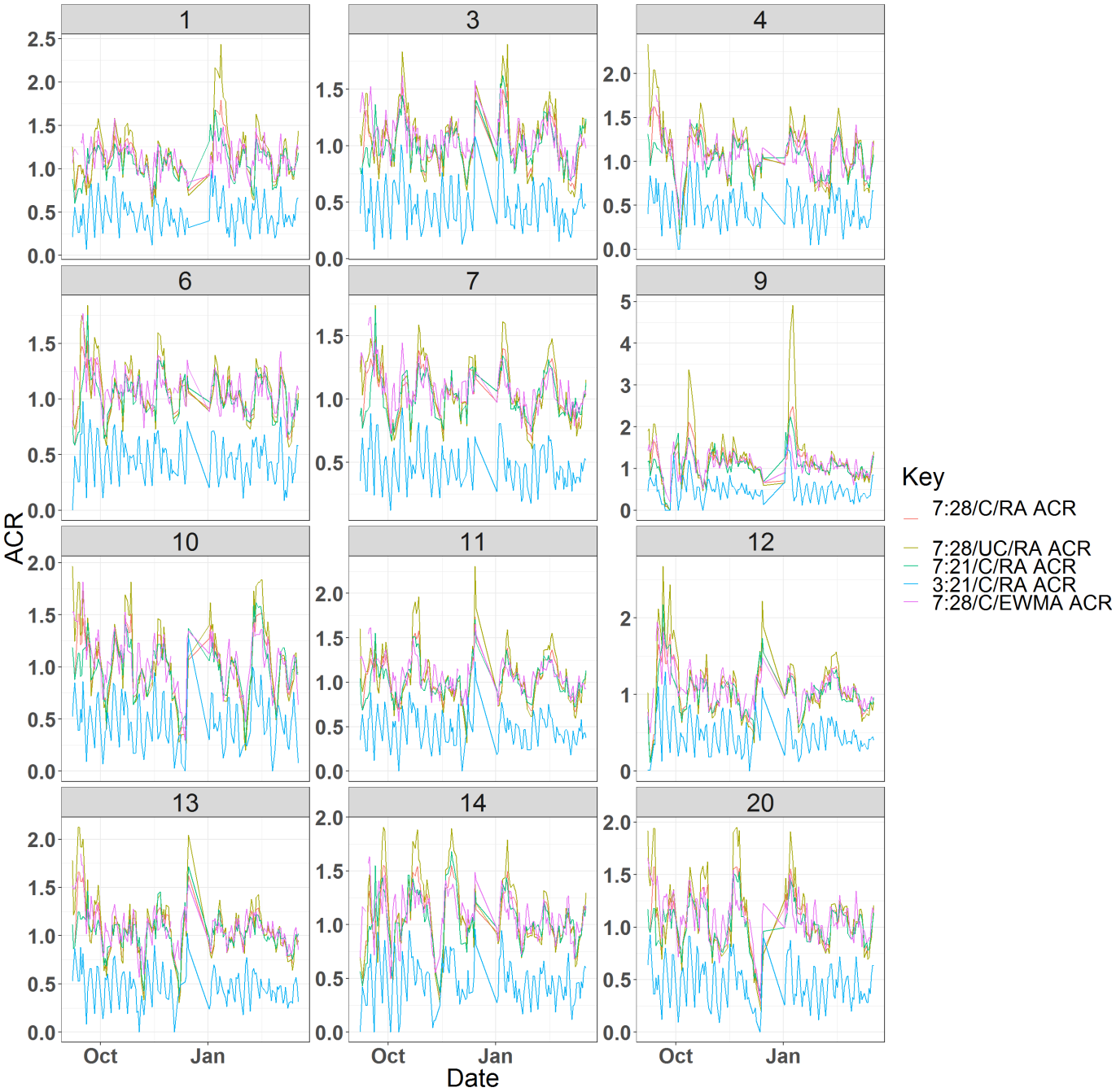

Figure 3.6 ACR variants across season for each player.

3.2.2.1 Modelling with ACR Variants

To compare the potential relationships between knee pain score and each of the ACR variants, we conducted mixed effect modelling using each of the ACR variants as a predictor in its own model of knee pain score. This modelling was done under a complete case analysis, with any missing observations that have missing data for the ACRs or knee pain score filtered out.

The results of this modelling, shown in Appendix U, indicate that the first three ACR variants have a similar effect on knee pain score. Their exponentiated coefficient estimates are around 1.05, implying a 5% increase in knee pain score for every 1 unit increase in ACR. The other ACR variants of 3:21/coupled/RA and 7:28/coupled/EWMA seem to have steeper relationships of around 1.08. However, these relationships do not appear to be statistically significant due to the high standard errors for these coefficient estimates. The 95% confidence intervals give us a better idea as to the effect of each ACR variant, with 95% confidence that the true effect of each ACR variant is contained within the intervals. For example, the first confidence interval indicates that we are 95% confident that the true effect of the 7:28/coupled/RA variant on knee pain score is between about -6.0% and 18% (the true exponentiated coefficient lies between 0.94 and 1.2). Overall, the results suggest that the ACR variants likely have a weak relationship with knee pain score on their own.

3.2.2.2 Modelling with ACR Variants and Fixed Additional Covariates

In the previous analysis, we only modelled each ACR variant against knee pain score. In this version of the analysis, we included a set of covariates that we would like to adjust for so that we can make comparisons between the effects of different ACR variants after the adjustment. We only included the main effects to prevent the models from becoming too complex, and we included the following variables: (1) position, (2) jump count, (3) average jump height, and (4) date. We avoided more complex models with interaction terms to both avoid overfitting and also because we cannot conduct variable selection while keeping the same covariates across all five models. One ACR variant's model may select different variables than another ACR variant's model if we conduct variable selection, preventing comparisons.

After fitting the models, we obtained similar results as in the previous analysis with each ACR variant acting as a single predictor (Appendix V). Although some of the exponentiated coefficient estimates changed slightly (and the coefficient estimate for 7:28/uncoupled/RA being nearly significant), examining the 95% confidence intervals reveal that we still have low precision when it comes to estimating the effect of each ACR variant. The coefficients of the other predictors also change marginally between different ACR variants used. The results imply that the relationships between ACR and knee pain score are not necessarily sensitive to the variant of ACR used, and that the strength of the relationship between ACR and knee pain score may be weak.

Chapter 4: Discussion

4.1 VERT Validation

4.1.1 Main Findings

The first specific aim of this study was to examine the accuracy of VERT landing impact values in university volleyball players. The results of the validation study show that VERT had an extremely high variability, as evidenced by the percentage differences with Shimmer as a reference, and there is a propensity for VERT to have measurements much lower than Shimmer. Hence, the validity of the VERT device's landing impact values can be said to be generally poor, with respect to Shimmer, when it comes to measuring landing impacts. This is contrary to our hypothesis that the absolute VERT landing impact values will fall within 10% of the landing impact values derived from the Shimmer.

As this study was the first to perform an external validation of VERT for the landing impact parameter, the main findings cannot be discussed in relation to previous literature. It was projected that the VERT would present values similar to the Shimmer, since we were measuring landing impact, something that is very precise and quantifiable. It was also unreasonable to expect both devices to be exactly the same or within 1-2% because of the likelihood of having some measurement error, due to differences in placement as well as different developers and engineers. Such a wide discrepancy was not expected and indeed surprising.

There are several factors at play that could explain the VERT's variability and lower measurements than the Shimmer. On the one hand, it is possible that the sampling rate of the VERT is not sufficiently high enough to meet the performance demands of volleyball. On the

other hand, the disparate nature of the data from each of the devices can also serve as an explanation for our results. While the VERT is separating the data through an unknown algorithm, the Shimmer is providing the full signal. Another consideration is that landing biomechanics likely differed both within and between individuals, whether it be differences in the amount of knee flexion or landing on one foot before the other. This slight asymmetry may have led to different acceleration values at the exact location of the VERT and Shimmer sensors. This possibility could be tested by placing two Shimmers side by side in the same positions as used for this study, and assessing the magnitude of difference.

While VERT may be acceptable for measuring jump height and jump count, the landing impact data may not be truthful and caution should be exercised with interpretation of this parameter until further validation studies are conducted.

Some discussion is warranted around the issue with the VERT-identified landing impact values. The VERT identifies a number of acceleration peaks for each jump-land cycle. This generally is seen as a cluster of vertical bars on the iPad. For the most part, each cluster consists of one yellow bar (VERT-identified landing impact) and the rest are all red bars (accelerations due to events other than landing). The yellow bar is the tallest in some instances, but this is not always the case. Neither does there seem to be any temporal pattern; in other words, the order of the red and yellow bars seems to be random for each cluster. The VERT also may show multiple yellow bars in a given cluster because of heel to toe landings, one foot hitting the ground before the other foot, or simply a hard landing with a subtle reverberation. For these reasons, we preferred to use the single highest acceleration peak for each cluster that appeared in the VERT data, regardless of the colour. Shimmer data was similar to the VERT data in that it also showed a number of acceleration peaks for each jump-land cycle. The difference was that there was no colour labeling in the Shimmer data. We used the single highest acceleration peak for each cluster that appeared in the Shimmer data. Based on our approach, we made the assumption that the highest magnitude acceleration from a jump-land cycle corresponds to landing. It is true that this may not always be the case, however an argument can be made that our assumption stands the majority of the time. A study that examined the application of force during the vertical jump,

in both children and adults, shows force-time curves that support our reasoning (Floria, Gómez-Landero, & Harrison, 2014).

4.1.2 Limitations

Force platforms, the gold standard for measuring forces, were not used in this study for validating the VERT and this presents a limitation. The primary reason for not using force platforms was related to a lack of feasibility. The force platforms in the Motion Analysis and Biofeedback Laboratory could not be moved elsewhere and the ceiling in the laboratory was too low for the jumping requirements of the study. In addition to this, the landing for each jump would need to be directly on the force plate and it would potentially max out with the great amount of force created by participants, posing more complications. Research-grade accelerometers, such as the Shimmer device, were a suitable and possibly better alternative for a few reasons. Firstly, the Shimmer presents raw data and does not use proprietary algorithms unlike the VERT. Secondly, the Shimmer has been compared with force platform data. A study comparing force calculated from the Shimmer device with force platform data found moderate to low levels of agreement and a consistent systematic bias between both technologies (Howard, Conway, & Harrison, 2014). Although this is not the ideal and desired outcome, this means the Shimmer could still be used as a proxy to infer how far off from the gold standard the VERT stands. In the study by Howard et al. (2014), the Shimmer generally overestimated peak forces compared to force platform data. If the Shimmer is overestimating, and the VERT is estimating lower than the Shimmer, the VERT may either be overestimating or underestimating compared to the gold standard force platform. A future study could be conducted to evaluate how the VERT performs in relation to the force platform. It should be noted that this validation study also served as a performance test of the VERT to verify that the accelerometers it contains are high enough performance for the demands of volleyball. Thirdly, the Shimmer has a portable computer so can be worn in a field setting. Lastly, the Shimmer may be placed at specific body parts. Placement at a desired location was advantageous as it allowed for precise measurement at a particular location, the center of mass in this case. The force platform, on the other hand, likely

would not have given the resultant peak acceleration at the center of mass, but rather at the feet before any dissipation of force upon travelling up the kinetic chain.

Another challenge we faced was the fact that the VERT algorithms, software utilized, acquisition of raw data, exact sampling rate, and filtering techniques are unknown. This made it difficult to select an appropriate sampling rate for the Shimmer, although we overcame this limitation by choosing the highest possible sampling rate. This was confirmed to be greater than the VERT sampling rate, making it possible for us to recognize if the VERT was underestimating at all. The proprietary nature of VERT also limited us from fully interpreting of our results.

While evidence-based guidelines were being followed to mitigate any potential interference between the two devices (e.g. avoiding placing one on top of the other), there was a chance that there was crosstalk when in close proximity at the level of the waist (Düking, Fuss, Holmberg, & Sperlich, 2018). Despite taking the steps to ensure the waist bands were fit snug and positioning the devices far apart to avoid bumping into each other, unwanted movement of the bands or devices may have still occurred without knowing.

The sample included was not balanced in terms of the genders that were represented. This is what was feasible, however, given the circumstances and recruitment. Ultimately, this did not interfere with the ability to compare the values from the two devices. The devices do not discriminate based on who is wearing them, how high they jump, shoes they are wearing, etc.

4.2 Pilot Examination of Player Data

4.2.1 Main Findings

The second specific aim of this study was to conduct an exploratory analysis of player data over the course of a university volleyball season, documenting player compliance, completeness and integrity of the data set, and documenting whether established relationships between load characteristics (sRPE, ACR, average jump height, jump count, time in season, player position) and knee pain scores are observed in this data set.

The results of the pilot examination of player data were shown by the exponentiated coefficient estimates in the linear mixed effect model, along with the visualizations of the model predictions. On the whole, the main effects of average jump height ($p=0.041$) and date ($p=0.032$) were negatively associated with knee pain score. This means that as average jump height and days into the season increased, knee pain score decreased. We cannot make any firm conclusions regarding the effects of ACR, jump count, and player position on knee pain score due to a lack of statistical significance, although there were apparent trends that as ACR and jump count increased, so did knee pain score. There was also a nonsignificant trend that setters and middle blockers reported higher knee pain scores than leftsides and opposites.

Having cognizance of this information, we should keep in mind that many of the coefficient estimates in the linear mixed effect model were quite small and statistically insignificant, suggesting that many of the predictors had only a minor effect (or no effect) on knee pain score. The only statistically significant main effects were deemed to be average jump height and date, showing that as average jump height and days into the season increased, knee pain score decreased. Note that sRPE was removed as a predictor in the linear mixed effect model due to the large number of missing values.

A scan of the past literature in this area uncovers general trends allowing us to understand the relationships between various load characteristics and a patellar tendinopathy diagnosis in athletes (with knee pain being a hallmark clinical feature of this condition).

Timoteo et al. (2018) looked at the influence of workload on injuries in elite male volleyball players, and found that greater odds of injury was related to higher ACR. Athlete's workloads were quantified by the sRPE multiplied by training session duration, and this was in turn used to formulate ACR. These findings informed our hypotheses that sRPE and ACR would be positively associated with knee pain score. In the present study, we observed a positive association between the 7:28/coupled/RA ACR variant and knee pain score, supporting this hypothesis, however the finding was not statistically significant. As mentioned, no inferences could be made regarding the association between sRPE and knee pain score due to the large subset of absent data.

Studies have demonstrated that volleyball players who jump higher during practice and matches may be more susceptible to develop patellar tendinopathy. Symptomatic individuals were found to have better jump performance compared to matched controls, as evidenced by significantly higher countermovement jump height and squat jump height (Helland et al., 2013; Håvard Visnes, Aandahl, & Bahr, 2013). These findings informed our hypothesis that average jump height would be positively associated with knee pain score. In the present study, we in fact found a negative association between average jump height and knee pain score, leading us to reject this hypothesis. Although contradicting the literature which cites the jumper's knee paradox, this finding is also intuitive because one would imagine that symptomatic athletes have worse jumping capability, due to the presence of their condition.

A high volume of volleyball training characterized by a high volume of jumps, as well as greater match exposure were found to be significant risk factors for developing patellar tendinopathy (Bahr & Bahr, 2014; H. Visnes & Bahr, 2013). These findings informed our hypotheses that

jump count and date would be positively associated with knee pain score. In the present study, we found a positive association between jump count and knee pain score, supporting this part of the hypothesis, however the finding was not statistically significant. Conversely, we found a negative association between date and knee pain score, rejecting that part of the hypothesis. This latter result, while unexpected, can be explained by considering the literature which indicates the beginning of the season as a time when players experience an abrupt increase in workload and, consequently, elevated injury rates (Gabbett, 2004; Gabbett & Jenkins, 2011; Killen, Gabbett, & Jenkins, 2010). Reasons for these findings are low fitness, low chronic workload, and spikes in weekly workload at the start of the season. As the season progressed, players may have gradually become accustomed to the workloads leading to less knee pain. The interaction with position should be considered and is thought provoking. Setters and middle blockers knee pain scores declined over the course of the season whereas leftsides and opposites reported more knee pain as the season progressed.

The majority of studies on the effect of player position on patellar tendinopathy in volleyball have concluded that middle blockers and leftsides have a higher incidence of patellar tendinopathy than the other positions (de Vries, van der Worp, Diercks, van den Akker-Scheek, & Zwerver, 2015; Øystein Lian, Refsnes, Engebretsen, & Bahr, 2003; Mahieu et al., 2011). Explanations offered include the tendency to be taller, heavier and jump higher when in these positions (Øystein Lian et al., 2003). These findings informed our hypothesis that middle blockers and leftsides would report the highest knee pain scores. In the present study, we found that middle blockers and setters reported the highest knee pain scores, which was partially consistent and partially inconsistent with our hypothesis, however the findings were not statistically significant. A potential explanation for this is the small sample size for each position (4 leftsides, 4 middle blockers, 2 opposites, 2 setters), therefore only representing a fraction of those in each position. Interestingly, a recent study by Skazalski et al. (2018) that was the first to examine position-specific jump demands among volleyball professionals found that setters performed the greatest volume of jumps compared to the other positions. This could also justify our findings because even though leftsides may jump higher than setters, perhaps the sheer volume of jumps performed by setters outweighs the height jumped.

A subcomponent of the pilot examination of player data involved investigating whether different results emerged when different methodological approaches were used to calculate ACR. When comparing ACR variants in terms of their effects on knee pain score, it was discovered that they were generally similar to one another, with the variants of 3:21/coupled/RA and 7:28/coupled/EWMA appearing to be slightly more sensitive than the others. This is interesting because a study experimenting with differing acute and chronic time windows found that a 3:21 days ratio performed better than the commonly used 7:28 days ratio in Australian footballers (Carey et al., 2017). Another study evaluating the relationship between different definitions of ACR and health problems found that it is dependent on the methodological approach, and the strongest association was observed with a 7:28/coupled/EWMA estimate (Dalen-Lorentsen et al., 2020). Overall in the present study however, the variant used did not have a major influence on the relationship with knee pain score, and the strength of the relationship between ACR and knee pain score was weak.

The findings discussed in this section contribute to the current understanding of patellar tendinopathy and its risk factors, allowing clinicians to provide more evidence-based advice to patients on how to self-manage their condition in order to remain physically active while promoting recovery. The practice of load monitoring is also supported and encouraged to reduce injury odds. Certainly, future research is needed to solidify the relationships between load characteristics and knee pain.

4.2.2 Limitations

The major limitation was the very small sample size of 16 players, undermining the internal and external validity of the study. As well, due to the exploratory nature of this analysis, we were limited in the conclusions we could draw, because we examined many different aspects of the

data. The point of this type of analysis was to identify correlations, and to hypothesize as to their cause, but not to form solid conclusions about cause and effect.

The method in which ACR was calculated can also be seen as a limitation. The calculation relied solely on jump count, a measure of external training load. It did not take into account a measure of internal training load, such as RPE, which may provide useful information on the physiological and psychological response to the external load.

A more complicated modelling procedure such as a time series would be more sensitive, better capture lag effects, and take into account that variable values in the past can affect values in the present. Nevertheless, this is outside the scope of this project, and a linear mixed effect model may be considered a valid approach and a step in the right direction (Windt et al., 2018).

It can be argued that the data set was slightly contaminated. The head coach of the UBC Men's Volleyball Team was looking at the data as it was being collected, and using this information to adjust practice regimens. This may be why some trends were not visible (e.g. there were no spikes in jump count and most ACRs were in the 0.8-1.3 optimal range).

There are inherent limitations to using pain scores on a scale that runs from 0-10. Some athletes probably reported higher pain scores even though may not be representative of true pain levels because of other stressors like school. Conversely, some athletes probably reported lower pain scores because they were desperate to play in upcoming games.

Finally, this study neglects other factors that could certainly be influencing the relationship between the load variables and knee pain, some of which include the type of flooring, footwear, and jump biomechanics.

4.3 Future Directions

There is clearly a rationale to continue the search for a wearable device that can accurately quantify landing impact in sports such as volleyball, where there is a high risk of injury due to repeated landing impacts. The VERT should not be ruled out, however, and more studies assessing its accuracy are called for, in order to make a sound judgement. It would also be interesting to look at a more recent VERT data set from the UBC Men's Volleyball Team, that includes the landing impact variable, and use linear mixed effect modelling to see if this variable relates to knee pain scores. At this stage, we do not know if landing impact is a superior parameter to jump count for managing loads in players who have, or who are at a risk of, patellar tendinopathy, but such an analysis would allow further insights. If the relationship between landing impact and knee pain does turn out to be statistically significant, one could progress from a retrospective to a prospective study. The prospective study could recruit two groups of athletes, with one group exposed to a high dose of impacts and the other group exposed to a low dose of impacts, to see the ensuing differences in knee pain. If the relationship between landing impact and knee pain does not turn out to be statistically significant, it would be interesting to consider other factors in the model such as over striding, flooring, and quad strength. This would contribute to enhancing our overall understanding around the relationships between load characteristics and knee pain, which is still evolving. Given the limitations of a pain scale that runs from 0-10, future studies may also attempt to capture knee pain in a more objective way. For example, it would be ideal if each player could undergo a clinical examination after each practice or match session. This examination could entail looking for the two hallmark features of patellar tendinopathy which are (1) pain localized to the inferior pole of the patella and (2) load-related pain that increases with the demand on the knee extensors, notably in activities that store and release energy in the patellar tendon (Peter Malliaras et al., 2015). Ultrasound could also be implemented to assess and potentially quantify aspects of tendon pathology.

4.4 Practical Recommendations

Based on the findings of the VERT validation study, coaches and practitioners should treat the VERT landing impact data cautiously. This certainly does not mean that the VERT is contraindicated, as it has proven to be valid and reliable for measuring jump height and jump count. In terms of the ACR variant of choice, I would recommend using the most traditional variant such that comparisons can be made with other teams, alongside the EWMA variant which has been shown in recent studies to perform better.

Chapter 5: Conclusion

In conclusion, the VERT landing impact values were more variable and had a propensity to be lower when compared to the same measurements taken from a research-grade accelerometer. Hence, the validity of the VERT device's landing impact values can be said to be generally poor, with respect to the Shimmer. In analyzing the VERT data set, relationships were indeed found between the various load characteristics and knee pain scores, although not fully consistent with what the previous literature has shown. On the one hand, ACR and jump count increased in tandem with knee pain score as expected, but these findings were not statistically significant. On the other hand, as average jump height and days into the season increased, knee pain score decreased (contrary to our expectations). Setters and middle blockers reported higher knee pain scores than leftsides and opposites, and this was also unforeseen and not statistically significant.

The VERT may be a useful tool for the practice of load monitoring, although the landing impact data may not be truthful and caution should be exercised with the interpretation of this parameter until further validation studies are conducted.

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Appendices

Appendix A Study Card

a place of mind
THE UNIVERSITY OF BRITISH COLUMBIA

CENTRE for HIP Health and Mobility

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HEALTHY VOLUNTEERS NEEDED!

We are recruiting male and female varsity volleyball players for a research study that will assess the validity of a recently developed vertical jump monitor called the VERT system. This information is important for developing small, wearable monitors which could be used to help volleyball players to train effectively.

What does participation involve?
Participation will involve one visit to War Memorial Gym (approx. 30 minutes) where you will be asked to perform a series of countermovement jumps with the wearable technology. You will be compensated with a $10 JJ Bean gift card at the completion of your study visit for your participation.

If you are interested and would like further details, as well as inclusion/exclusion criteria, please contact:

Faraz Damji BKIN
MSc Candidate, Rehabilitation Sciences
[redacted]

Using the VERT wearable device to examine resultant peak acceleration at the center of mass during impact landing
Version date: 28th November 2019

Appendix B Data Collection Sheet

Using the VERT wearable device to examine resultant peak acceleration at the center of mass during impact landing

Data Collection Sheet

Study ID: _____

standing reach height = _____

Block 1: Maximal Countermovement Jumps

	VERT – waist Landing impact (G) from iPad	VERT – waist Landing impact (G) from excel To be filled in later	SHIMMER – waist Landing impact (G) To be filled in later
Trial 1			
Trial 2			
Trial 3			
Trial 4			
Trial 5			

highest vane displaced from block 1 = _____

_____ (highest vane displaced) – _____ (standing reach) = _____ (max jump height)

_____ (max jump height) x 0.8 + _____ (standing reach) = _____ (submax jump target)

Block 2: Submaximal Countermovement Jumps at 80% max

	VERT – waist Landing impact (G) from iPad	VERT – waist Landing impact (G) from excel To be filled in later	SHIMMER – waist Landing impact (G) To be filled in later
Trial 1			
Trial 2			
Trial 3			
Trial 4			
Trial 5			

Appendix C Participant Questionnaire

Using the VERT wearable device to examine resultant peak acceleration at the center of mass during impact landing
Questionnaire

Study ID: _____

Body Weight in kg: _____

Age on Assessment Day: _____

Sex: M/F: _____

Standing Height in cm: _____

		YES	NO
1a	Have you had any severe injury affecting the lower extremity in the past twelve months? This includes any **orthopedic injuries** (i.e. injuries to the musculoskeletal system including bones, joints and soft tissues such as muscles, tendons and ligaments) with **significant structural damage** (e.g. ACL tears, fractures, chondral injuries) or **requiring surgery**, in the **past twelve months**.		
1b	Do you have articular or muscle pain in the legs?		
1c	Do you currently have a diagnosis of patellar tendinopathy?		
1d	If you answered yes to any one of the above questions (1,2,3), has a doctor or other health professional told you to avoid all jumping activities?		
2a	Do you currently have any musculoskeletal symptoms? E.g. pain, weakness, stiffness, joint noises, decreased range of motion		
2b	If yes, what symptoms do you have? If it is linked to a previous injury please specify		
3a	Have you participated in strenuous exercise in the last 24 hours?		
3b	If yes, what did you do? E.g. 1 hour of soccer		
4	Which leg is your dominant leg?		
5	What position do you play in volleyball?		
6	How often do you train in volleyball (number of sessions and hours per week)?		
7	What level do you compete at (professional/national, competitive college level, recreational)?		
8	Jumping / landing leg – **to be filled in by study coordinator**		

Appendix D Oslo Sport Trauma Research Centre-Patellar Tendinopathy (OSTRC-P) Questionnaire

Please answer all questions regardless of whether or not you have problems with your knees. Select **(tick or circle)** the option that is most appropriate for you, and in the case that you are unsure, try to give an answer as best you can anyway.

The term "knee problems" refers to pain, ache, stiffness, swelling, instability/giving way, locking or other complaints related to one or both knees. Please note that all questions in this questionnaire refer to the previous week.

Question 1 - Have you had any difficulties participating in normal practice and game due to knee problems this past week?

a) Full participation without knee problems c) Reduced participation due to knee problems
b) Full participation but with knee problems d) Cannot participate due to knee problem

Question 2 - To what extent have you reduced your practice volume due to knee problems this past week?

a) No reduction b) To a minor extent c) To a moderate extent
d) To a major extent e) Cannot participate at all

Question 3 - To what extent have knee problems affected your performance this past week?

a) No effect b) To a minor extent c) To a moderate extent
d) To a major extent e) Cannot participate at all

Question 4 - To what extent have you experienced knee pain related to playing ~~basketball~~ volleyball this past week?

a) No pain b) Mild pain c) Moderate pain d) Severe pain

** If you answered "a" to all 4 questions, questionnaire is completed for the week; if otherwise please answer the following questions:*

Question 5 – Do you still experience any knee pain, especially during and/or after ~~basketball~~ volleyball participation?

a) Yes b) No **If "yes" please proceed to Question 6, if otherwise questionnaire is completed*

Question 6 - Is the knee pain you are reporting?

a) The same knee pain as in previous week(s) b) A return of a knee pain that had gone away
c) A knee pain that is being experienced for the first time this past week

Question 7 - On which knee do you have pain?

a) Right knee b) Left knee c) Both knees (right and left)

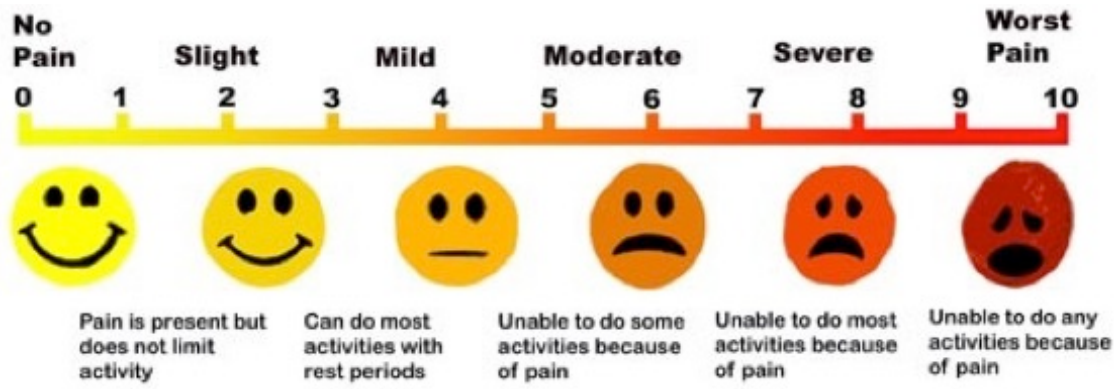
Complete this section as applicable		
	Right knee	**Left knee**
Question 8 Describing the onset of your knee pain, was it:	**a)** Of a gradual or sudden onset that is **unidentifiable** with any event? **b)** Of a sudden onset that is **clearly identifiable** (e.g. impact or collision with another player)?	**a)** Of a gradual or sudden onset that is **unidentifiable** with any event? **b)** Of a sudden onset that is **clearly identifiable** (e.g. impact or collision with another player)?
If your answer to Question 8 is "a" please proceed to Question 9, if otherwise questionnaire is completed		
Question 9 Describe the location of your knee pain (you can select multiple):	**a)** Front of the knee **b)** Back of the knee **c)** Inside of the knee (medial) **d)** Outside of the knee (lateral)	**a)** Front of the knee **b)** Back of the knee **c)** Inside of the knee (medial) **d)** Outside of the knee (lateral)
If your answer to Question 9 is "a" please proceed to Question 10, if otherwise questionnaire is completed		
Question 10 Is the pain in the front of your knee on the bottom tip of your kneecap?	**a)** Yes **b)** No	**a)** Yes **b)** No

FIGURE 1. The OSTRC-patellar tendinopathy questionnaire: adapted OSTRC Overuse Injury Questionnaire for patellar tendinopathy. Abbreviation: OSTRC, Oslo Sports Trauma Research Center. Adapted from Clarsen et al,[5] with permission from BMJ Publishing Group Ltd. Copyright ©2012 BMJ Publishing Group Ltd.

Appendix E Rating of Perceived Exertion (RPE)

Rating of Perceived Exertion (RPE Scale)	
10	Maximal
9	Really, Really, Hard
8	Really Hard
7	
6	Hard
5	Challenging
4	Moderate
3	Easy
2	Really Easy
1	Rest

Appendix F Pain Scale



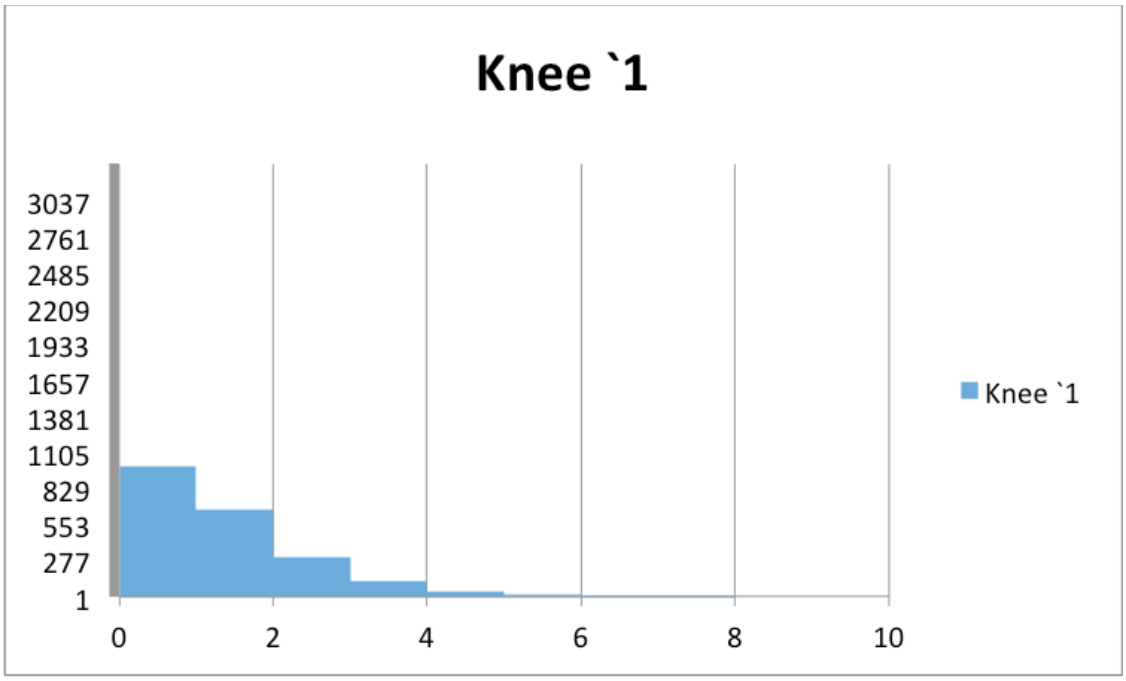
Appendix G VERT Data

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W
1	Date	Week	Player #	Position	Training Type	Jump Count	Average Jump Height	Average High	Duration (hr)	Duration (min)	Shoulder	Back	Knee	Other	Other #	RPE	sRPE	28 Day Rolling Average	7 Day Rolling Average	28 day Sum	7 Day Sum	ACR	RPE x Duration
2690	2/9/2017	Week 25	1	Setter	practice	85	15.3	18.3	2	120	1	2	3			1	120	114	80	3180	558	0.70	2
2691	2/9/2017	Week 25	3	Setter	practice	144	17.3	23.1	2	120	0	0	0			3	360	89	93	2495	651	1.04	6
2692	2/9/2017	Week 25	9	Middle	practice	90	23.2	28.6	2	120	0	1	3			4	480	77	67	2154	470	0.87	8
2693	2/9/2017	Week 25	13	Middle	practice	115	24.5	31.5	2	120	1	0	2			5	600	69	78	1923	547	1.14	10
2694	2/9/2017	Week 25	20	Middle	practice	99	19.6	27.9	2	120	0	0	2			5	600	81	64	2257	451	0.80	10
2695	2/9/2017	Week 25	10	Middle	practice	101	21.9	27.8	2	120	0	1	1	N	2	3	360	46	67	1290	472	1.46	6
2696	2/9/2017	Week 25	4	Leftside	practice	33	25.2	32.2	2	120	0	0	3	F	3	3	360	72	46	2020	323	0.64	6
2[illegible]	2/9/2017	Week 25	14	Opposite	practice	89	25.6	31.5	2	120	0	0	2	C	4	4	480	78	67	2194	467	0.85	8
2698	2/9/2017	Week 25	6	Leftside	practice	70	25.4	32.9	2	120	3	0	0			5	600	65	56	1829	395	0.86	10
2699	2/9/2017	Week 25	11	Leftside	practice	112	23.4	27.4	2	120	0	0	0			7	840	64	66	1792	465	1.04	14
2700	2/9/2017	Week 25	12	Leftside	practice	112	23.2	27	2	120	0	0	0			4	480	54	66	1509	462	1.22	8
2701	2/9/2017	Week 25	7	Opposite	practice	92	26.7	29.7	2	120	0	0	1			4	480	61	58	1716	404	0.94	8
2702	2/9/2017	Week 25	17	Libero	practice	0			2	120	0	3	0			3	360	0	0	0	0		6
2703	2/9/2017	Week 25	2	Libero	practice	0			2	120	0	0	1			3	360	0	0	0	0		6
2704	2/9/2017	Week 25	5	Libero	practice	0			2	120	0	0	0			2	240	0	0	0	0		4
2705	2/9/2017	Week 25	16	Libero	practice	0			2	120	0	0	0	W	2	2	240	0	0	0	0		4
2706	2/10/2017	Week 25	1	Setter	Match	240	17.3	28.3	3	180	3	2	1	AC	2	5	900	111	114	3119	798	1.02	15
2707	2/10/2017	Week 25	3	Setter	Match	138	18.8	22.4	1.5	90	0	0	0			3	270	90	98	2531	689	1.09	5
2708	2/10/2017	Week 25	9	Middle	Match	138	23.5	29.1	3	180	0	0	2			4	720	75	76	2103	530	1.01	12
2709	2/10/2017	Week 25	13	Middle	Match	82	21.5	32.6	1	60	0	0	3			1	60	69	73	1918	511	1.07	1
2710	2/10/2017	Week 25	20	Middle	Match	143	20.3	29.8	3	180	0	0	3			5	900	78	73	2186	512	0.94	15
2711	2/10/2017	Week 25	10	Middle	Match	46	17.6	30	1	60	1	0	1			2	120	48	64	1336	446	1.34	2
2712	2/10/2017	Week 25	4	Leftside	Match	132	24.5	32.1	3	180	1	0	2	F	2	5	900	70	54	1954	380	0.78	15
2713	2/10/2017	Week 25	14	Opposite	Match	120	24.6	30.3	3	180	0	0	0			3	540	75	72	2108	507	0.96	9

Appendix H Percentage of Missing Data for Each Variable

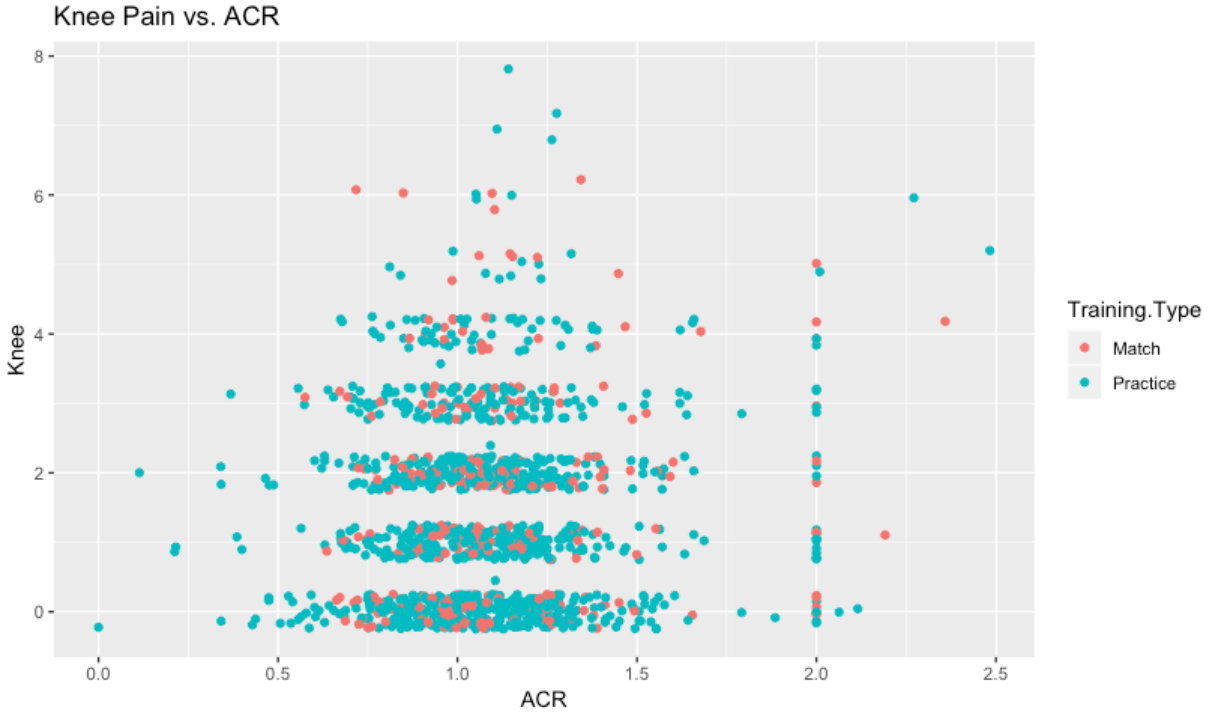
```
      [,1]                  [,2]
 [1,] "Date"                "0"
 [2,] "Week"                "0"
 [3,] "Player.."            "0"
 [4,] "Position"            "0"
 [5,] "Training.Type"       "0"
 [6,] "Jump.Count"          "0.0729885057471264"
 [7,] "Average.Jump.Height" "0.26264367816092"
 [8,] "Duration..min."      "0"
 [9,] "Knee"                "0.186781609195402"
[10,] "RPE"                 "0.638505747126437"
[11,] "sRPE"                "0.640804597701149"
[12,] "ACR"                 "0.0333333333333333"
```

Appendix I Number of Observations vs. Knee Pain

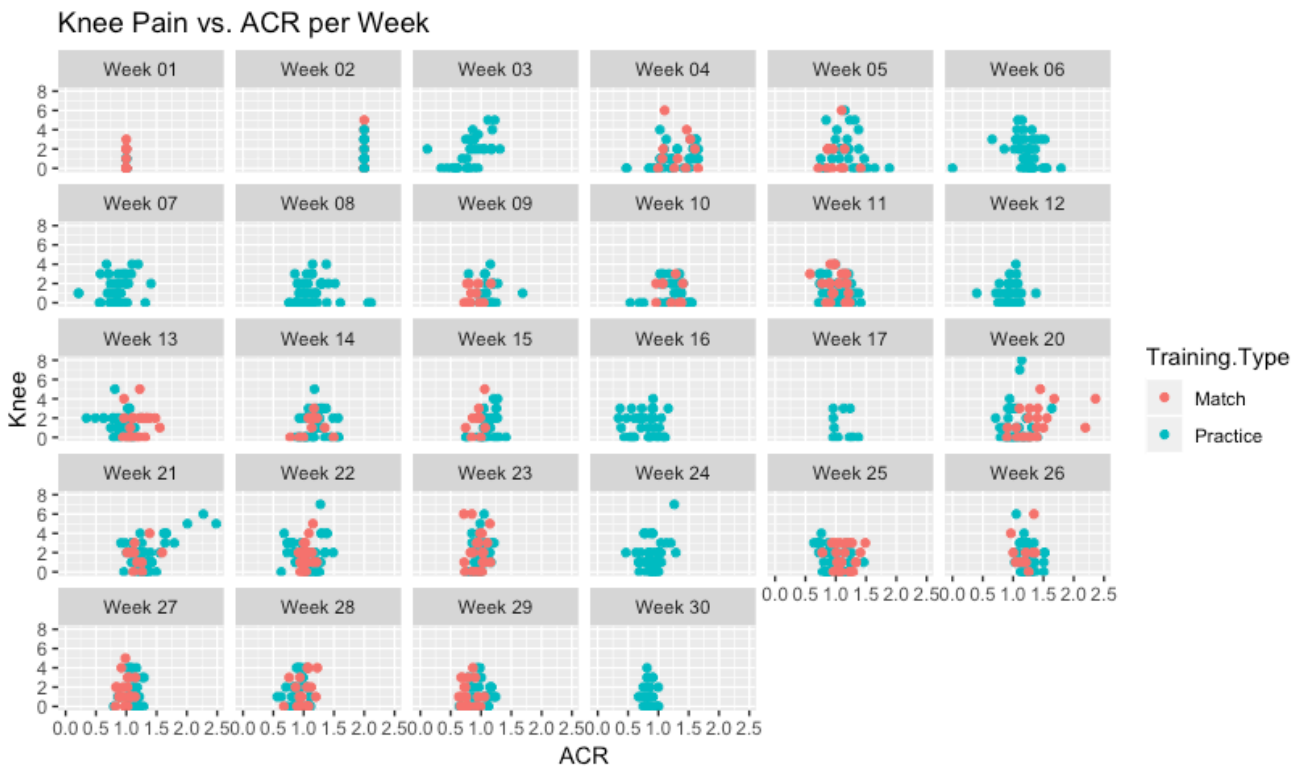


It can be observed that there are very few measures of knee pain higher than 4, and very many zeros.

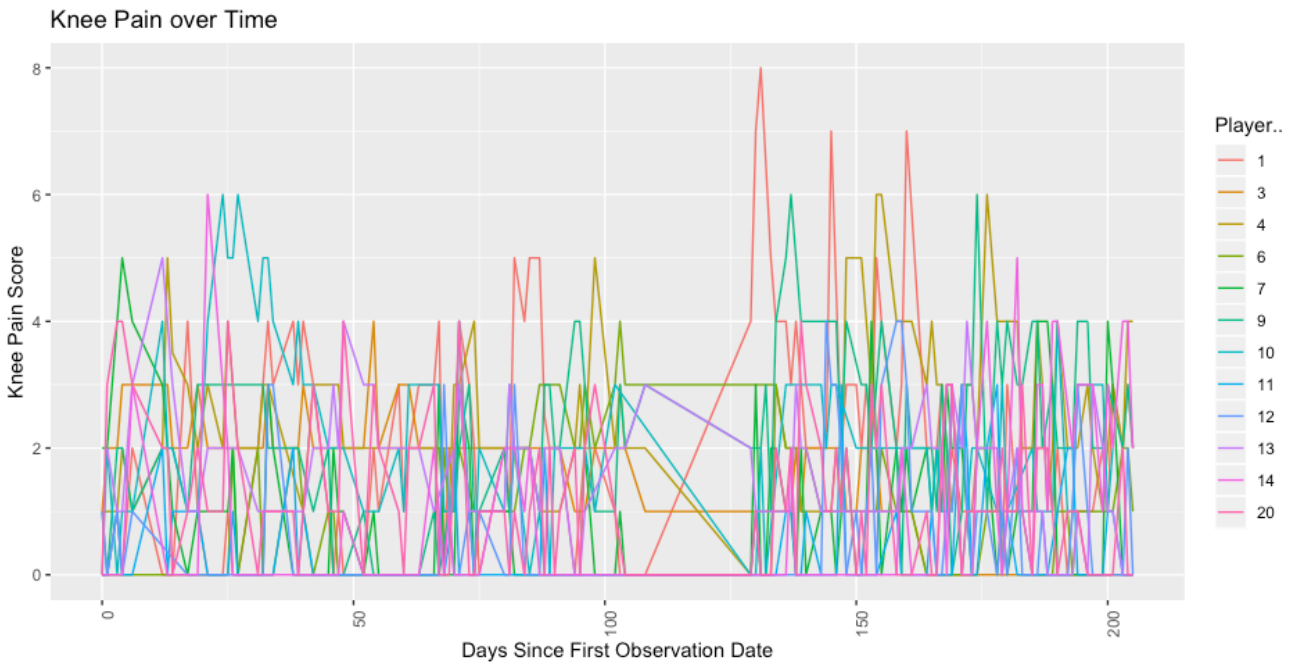
Appendix J Knee Pain vs. ACR



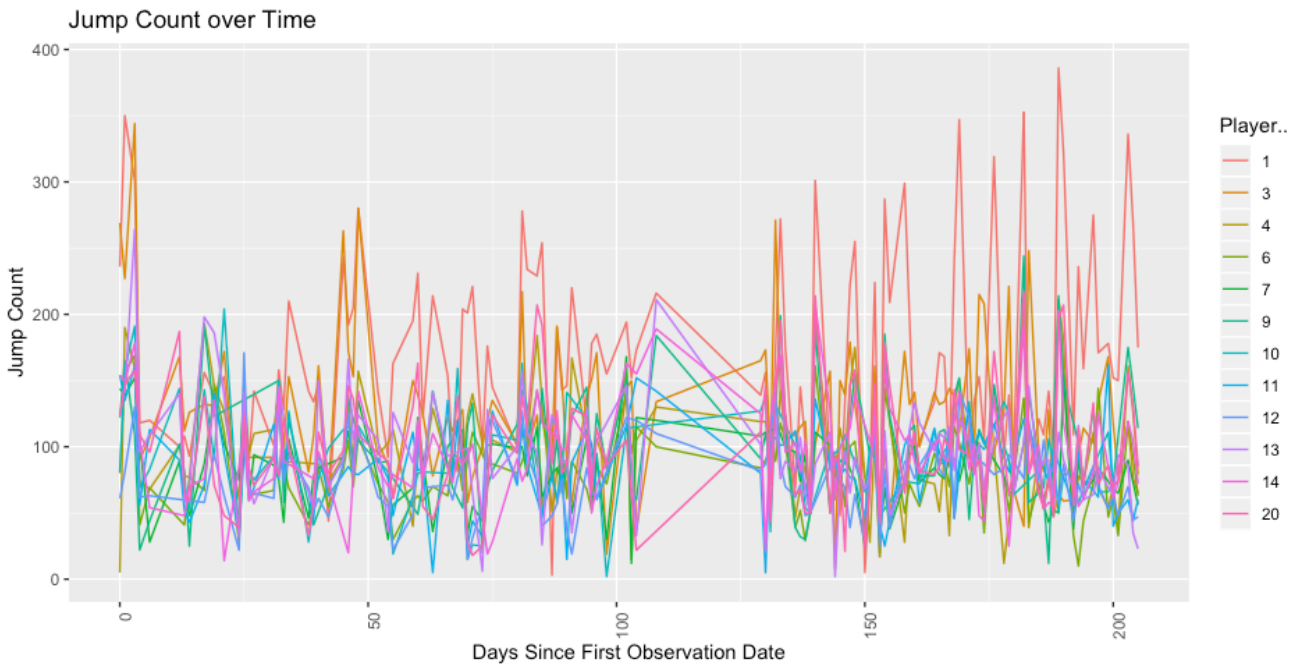
Appendix K Knee Pain vs. ACR Per Week



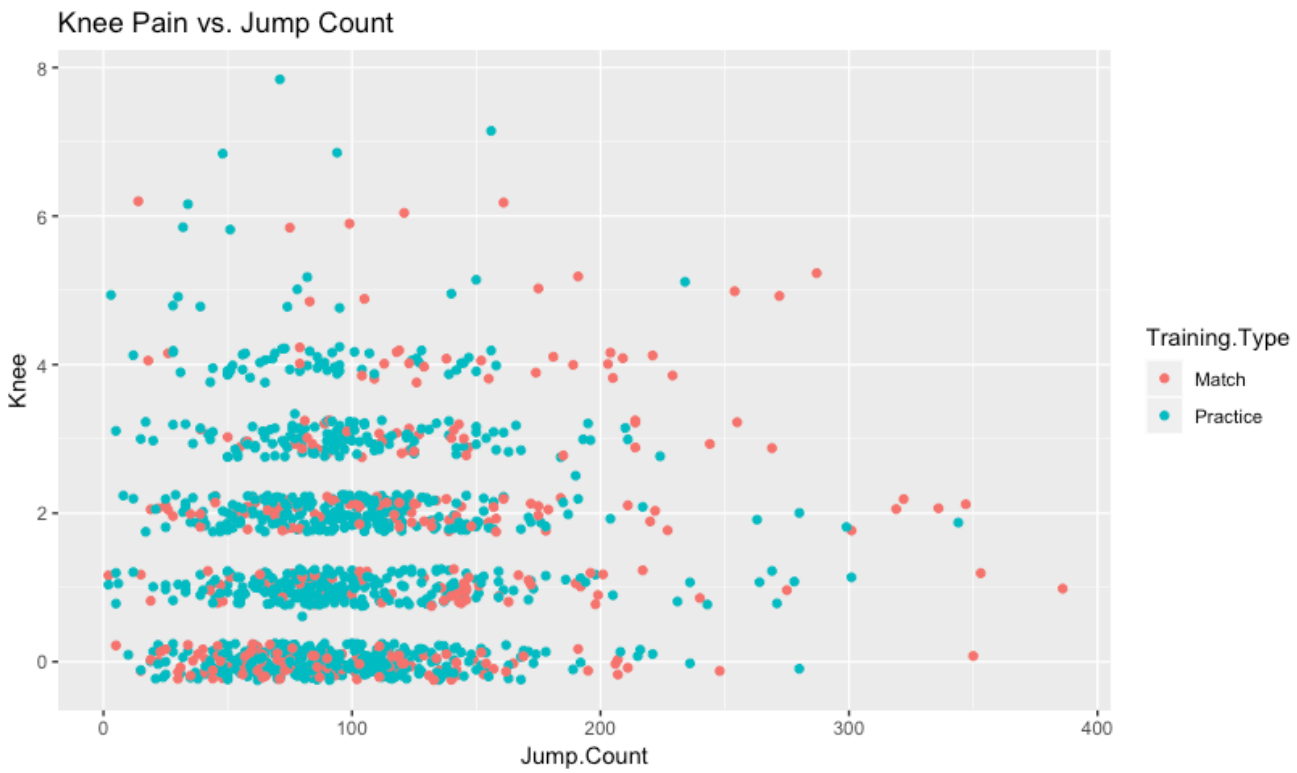
Appendix L Knee Pain Over Time



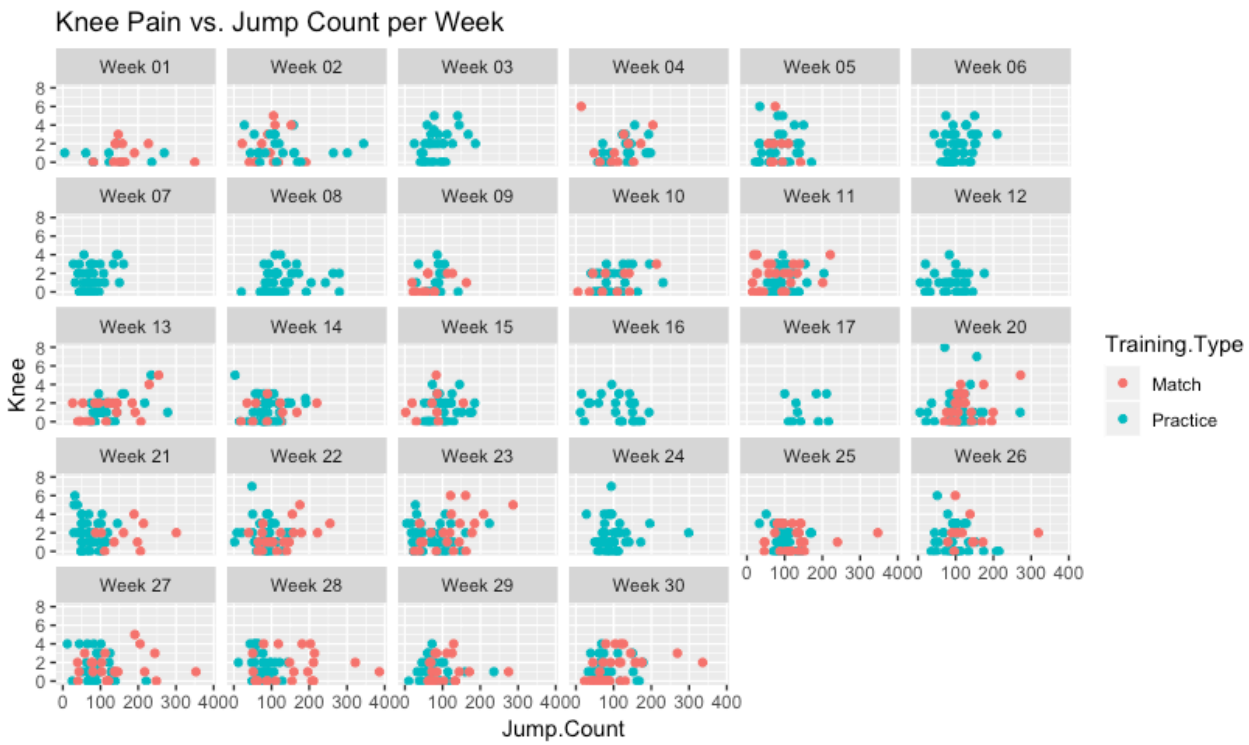
Appendix M Jump Count Over Time



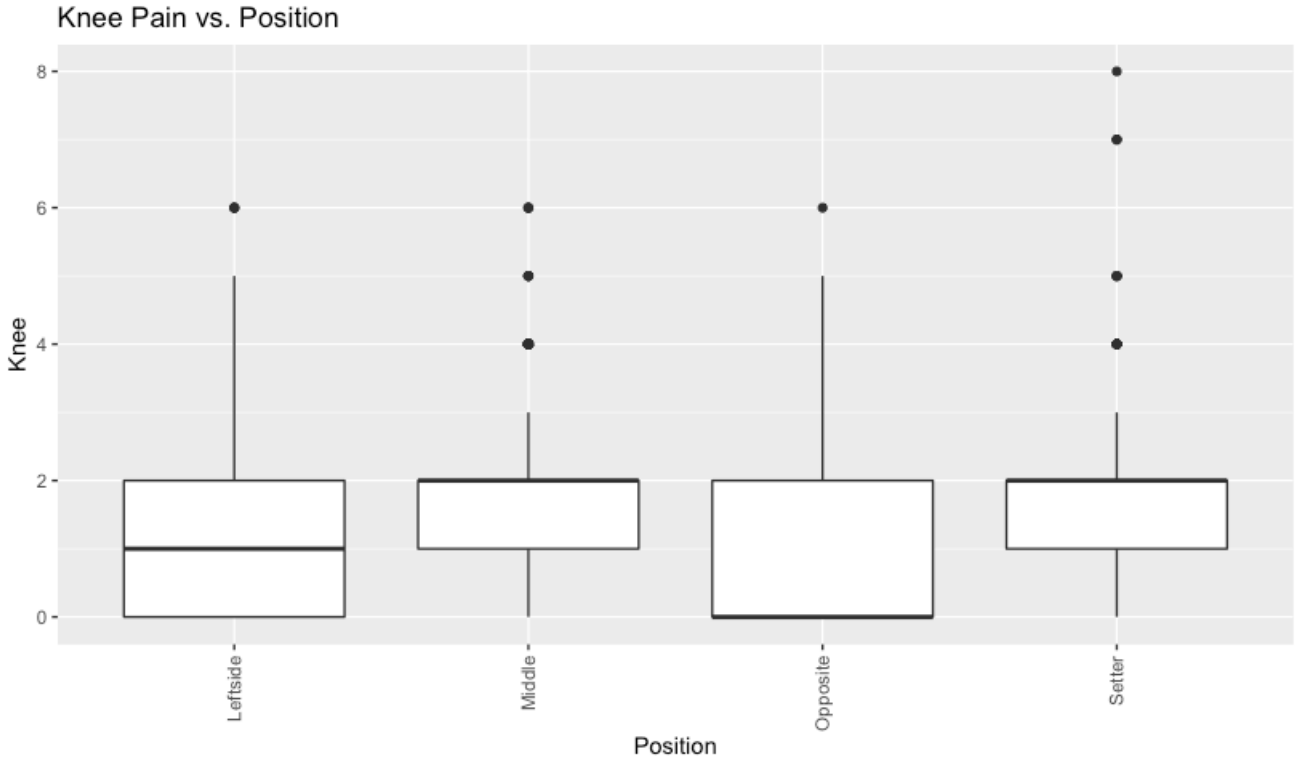
Appendix N Knee Pain vs. Jump Count



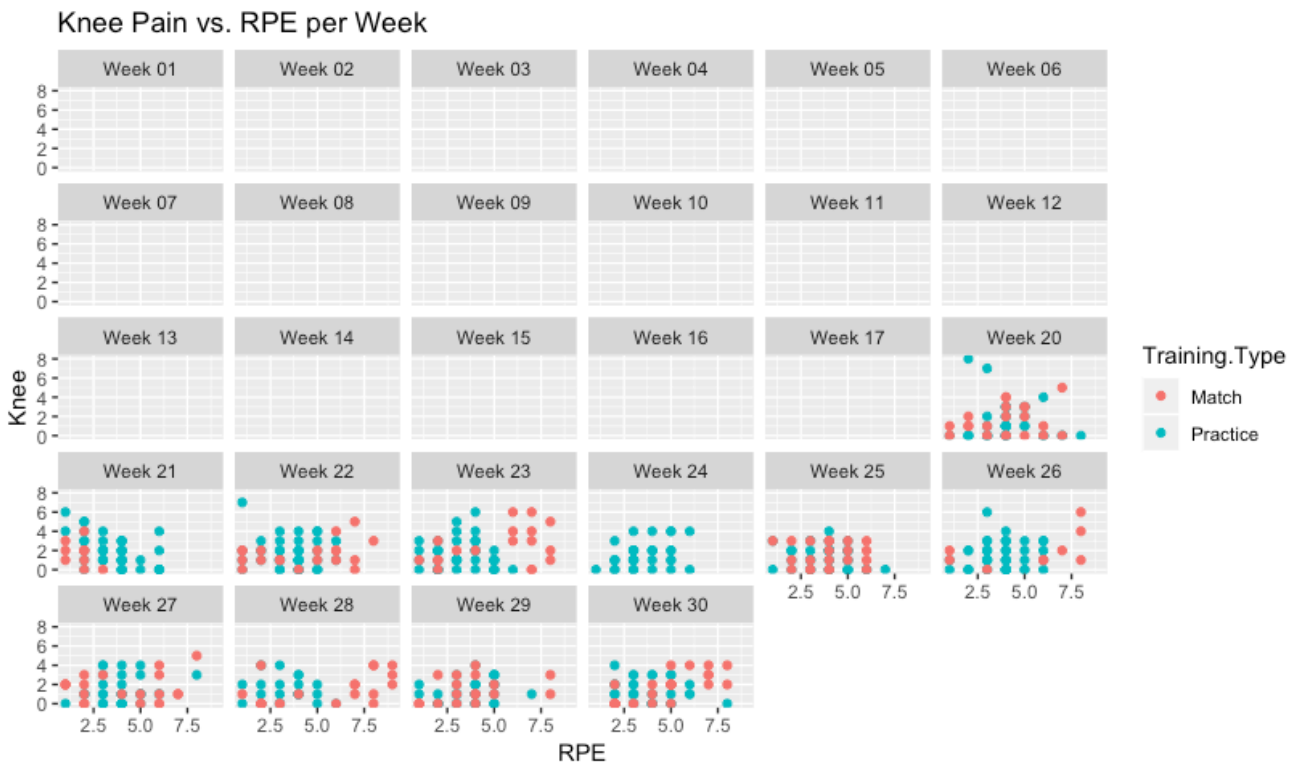
Appendix O Knee Pain vs. Jump Count Per Week



Appendix P Knee Pain vs. Position



Appendix Q Knee Pain vs. RPE Per Week

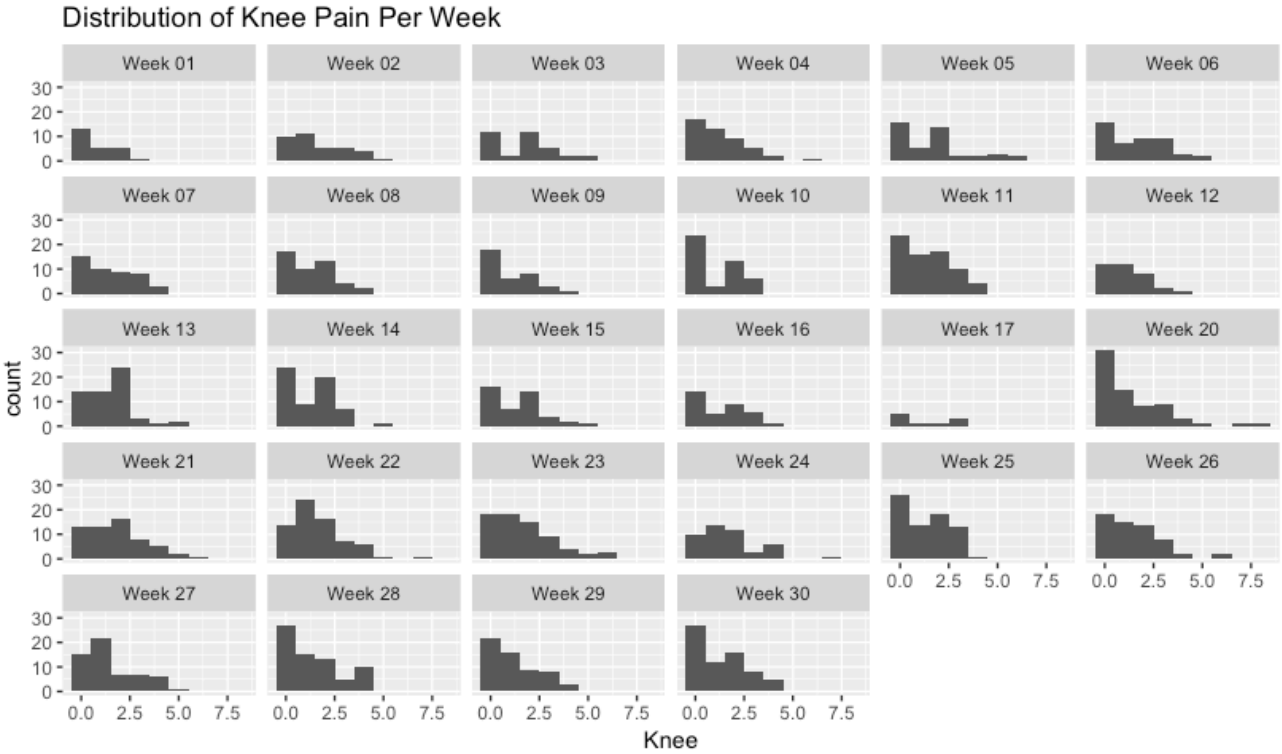


Appendix R Summary Statistics of Data Set

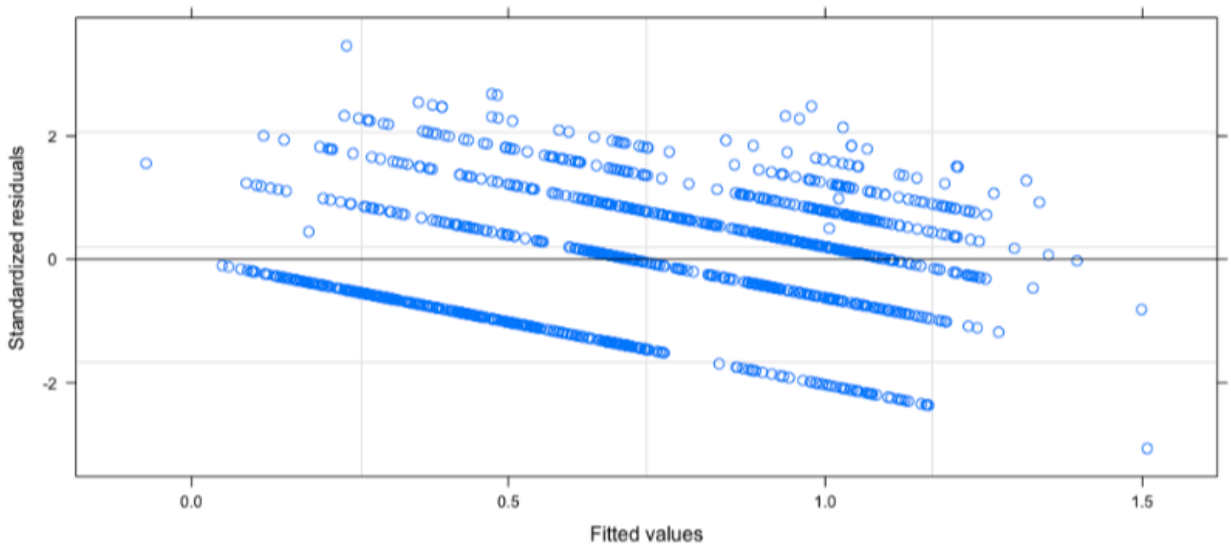
	MIN	MEAN	MAX
Jump Count	1.00	98.79	386.00
Average Jump Height	10.70	21.83	33.90
Knee	0.00	1.40	8.00
RPE	1.00	3.84	9.00
sRPE	60.00	481.30	1620.00
ACR	0.00	1.07	2.48

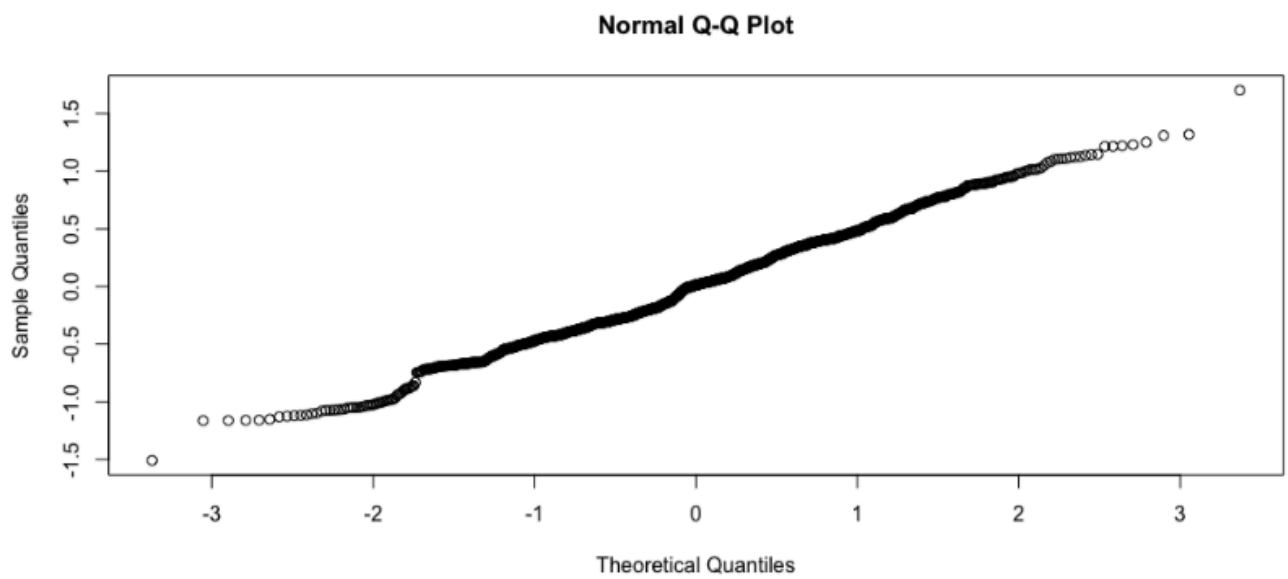
	Number of players	Mean Jump Count (practices)	Average Weekly Jump Count (practices)	Mean Jump Height	Mean Duration (matches)	Mean RPE	Mean sRPE	Mean ACR
Players who NEVER felt a pain of 4 or more	1	82.8	258	21.2	94.2	3.33	374	1.05
Players who HAVE felt a pain of 4 or more	11	100	1628	21.9	119	3.88	489	1.07

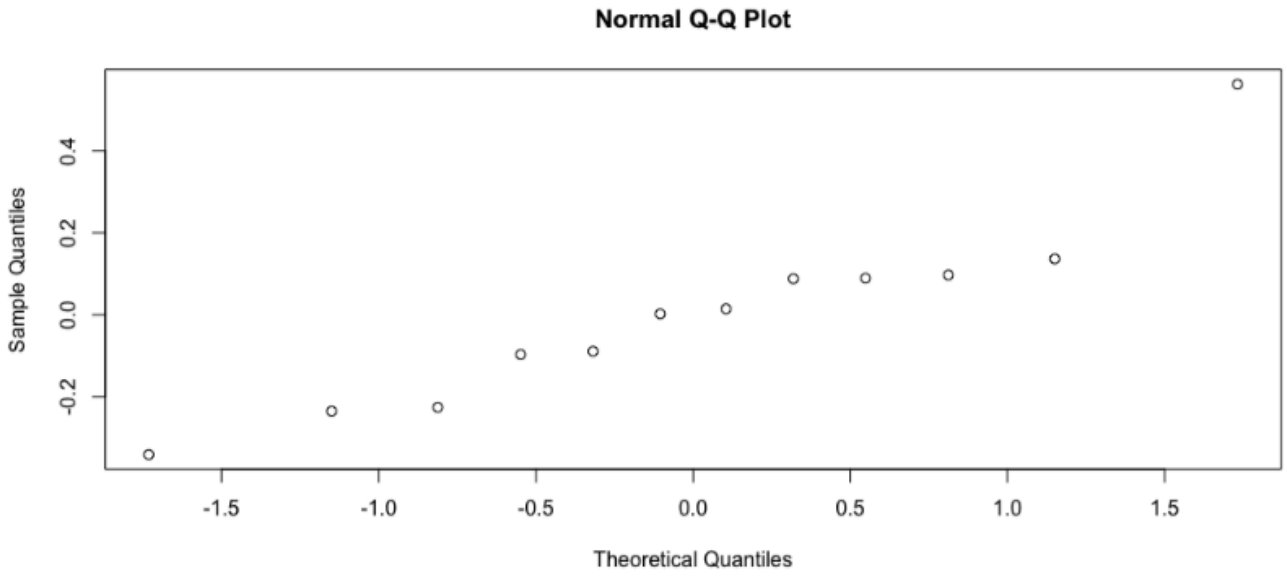
Appendix S Distribution of Knee Pain Per Week



Appendix T Diagnostic Plots for Linear Mixed Effect Model






Normal Q-Q Plot
Sample Quantiles
-0.2
0.0
0.2
0.4
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
Theoretical Quantiles

Appendix U Coefficients for ACR Variants and 95% Confidence Intervals (Single Covariate Models for Knee Pain Score)

	Coefficient Estimate (Exponentiated)	**95% Confidence Interval**	**Standard Error**	**p-value**
7:28/coupled/RA ACR	1.050	0.938 – 1.176	0.058	0.394
7:28/uncoupled/RA ACR	1.044	0.971-1.122	0.037	0.244
7:21/coupled/RA ACR	1.054	0.935-1.189	0.061	0.388
3:21/coupled/RA ACR	1.077	0.946-1.226	0.066	0.261
7:28/coupled/EWMA ACR	1.080	0.942-1.238	0.070	0.268

Appendix V Coefficients for ACR Variants and 95% Confidence Intervals (Multiple Covariate Models for Knee Pain Score)

	Coefficient Estimate (Exponentiated)	**95% Confidence Interval**	**Standard Error**	**p-value**
7:28/coupled/RA ACR	1.082	0.947-1.236	0.068	0.249
7:28/uncoupled/RA ACR	1.081	0.995-1.175	0.043	0.068
7:21/coupled/RA ACR	1.055	0.915-1.217	0.073	0.460
3:21/coupled/RA ACR	1.068	0.908-1.257	0.083	0.428
7:28/coupled/EWMA ACR	1.118	0.913-1.371	0.104	0.282

Appendix W Comparison of VERT and Shimmer Landing Impacts (VERT-Identified Landing Impacts)

Summary statistics of the devices can be found in Table 5.1. We observe that the summary statistics for VERT values are all lower than that of the Shimmer.

	Mean (G)	SD (G)	Max (G)	Min (G)
VERT	5.5	1.7	13.6	2.9
Shimmer	9.7	4.0	21.2	4.1

Table 5.1 Summary statistics of devices (VERT-identified landing impacts). SD = standard deviation.

Athletes were measured using the VERT device and Shimmer device simultaneously during a set of 10 jumps each, 5 maximal and 5 submaximal. A total of 14 volleyball athletes served as participants, 11 male and 3 female. The landing impact was measured by the resultant acceleration experienced by the athlete upon landing from a jump.

Please note that some data is missing in this version of the analysis. One of the participants does not have VERT-identified landing impact values. Additionally, 5 other participants are missing one VERT-identified landing impact value out of 10, thus having only 9 values total. The results that follow are based on a complete case analysis with omission of the observations with missing values.

The results of the analysis are shown in the histogram and Bland-Altman plot below (Figures 5.1 and 5.2). The histogram of percentage differences reveals that a large majority of the VERT measurements are lower than the Shimmer measurements, with percentage differences nearly all

between -75% and 0%. Rarely do a few of the VERT measurements exceed the Shimmer measurements. Overall we observe high variability from the initial histogram.

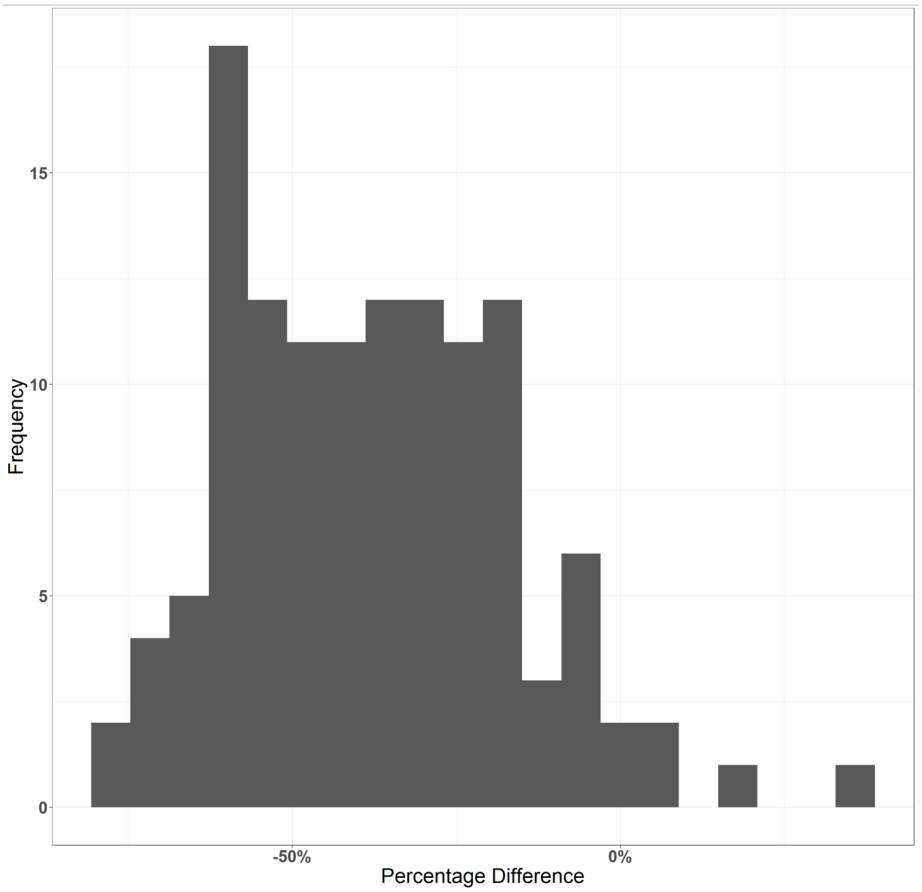


Figure 5.1 Histogram of VERT and Shimmer percentage differences (VERT-identified landing impacts).

The Bland-Altman plot shows similar results as observed in the histogram but with greater detail. On the y-axis is the percentage differences, and on the x-axis is the mean of the pair of measurements. Points are colour-coded by player and the red line represents the 0% difference mark. The blue line represents the mean bias, or the mean percentage difference we observe between VERT and Shimmer. No weighting is required for this method, even with an imbalance in repeated measures per subject. The dotted lines around the mean bias represent the 95%

confidence interval. Lastly, the green lines represent limits of agreement, which are the (mean bias)+1.96*(standard deviation of differences) and (mean bias)-1.96*(standard deviation of differences). Since we anticipate that the differences are normally distributed and we do not see severe deviance from normality in the histogram, then we anticipate that 95% of the differences fall within this range. This is approximately observed in the plot.

There are two primary features to be examined in the Bland-Altman plot, the variability of differences (reflected by the limits of agreement and the distribution of points) and the mean bias. The limits of agreement are remarkably wide, with limits of -81.76% and 5.42%, suggesting that percentage differences between VERT and Shimmer can vary by a large amount. This makes one question the validity of the VERT device when it comes to measuring landing impacts. Additionally, when examining the mean bias, we observe that its value is -38.17%. The confidence interval spans from -51.01% to -25.33%. As it does not overlap whatsoever with 0%, it indicates that the VERT device severely underestimates the landing impact value. Thus, there is a tendency for VERT to have lower measurements than Shimmer, resulting in a bias.

In examining the distribution of points themselves, it is evident that when the mean between the pairs of measurements is less than 10, then the points are nearly evenly distributed around the mean bias. When the mean of a measurement pair exceeds 10, the majority of measurements fall under the mean bias. This is evidence of lower reliability, and hence validity, of the VERT device landing impacts on the higher end of the spectrum. We observe a handful of outliers that exceed 0% difference and go above the upper limit of agreement (notably, most are from Player 12). Otherwise, the large majority of points fall within the limits of agreement.

With respect to the effect of player, there do not appear to be any notable relationships, although we do see clustering of points for some players such as for players 12 and 14, suggesting consistency in measurements for some players. In contrast, percentage differences for player 11 seem to be widely scattered. Additionally, with respect to the effect of jump type, there is no clear relationship with percentage differences from the plot itself.

Overall, this analysis reveals that the validity of the VERT device as a suitable alternative to Shimmer for the measurement of landing impact in volleyball players seems to be generally poor, with high limits of agreement indicative of high variability in percentage differences.

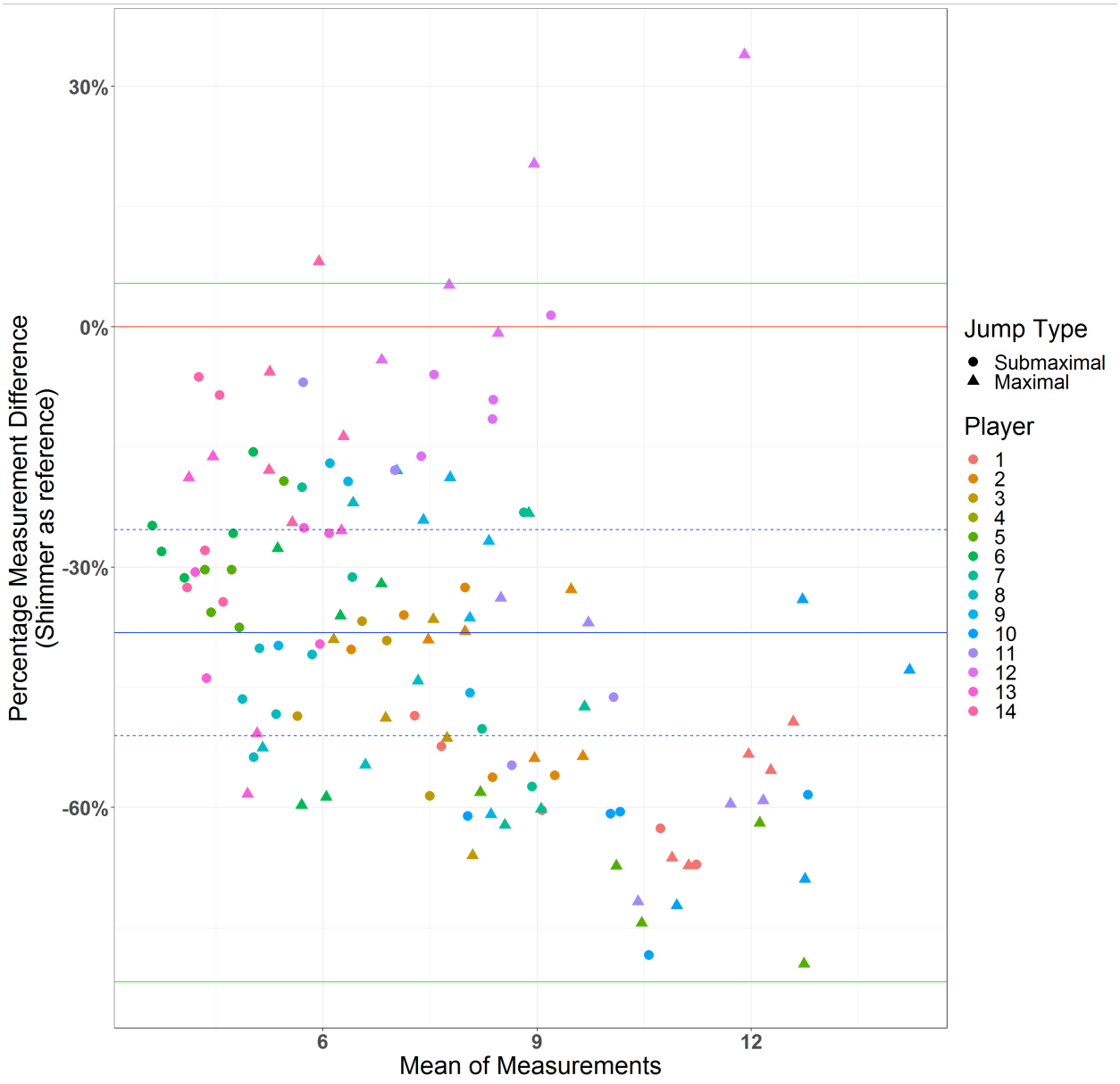


Figure 5.2 Bland-Altman plot for VERT and Shimmer agreement (VERT-identified landing impacts).

The calculated ICC is 0.3008, using the ICC for a two-way mixed effect model, single measures, and absolute agreement (McGraw & Wong, 1996). We are 95% confident that the ICC is between 0.1688 and 0.4222. The small size of the ICC value indicates mild agreement between the two devices. Thus, when using the VERT-identified landing impacts, the VERT device is a poor substitute for the Shimmer device. The calculated CCC is 0.1217. We are 95% confident that the CCC is between -0.0774 and 0.3114. The very small size of the CCC value corroborates what we observe with the ICC value, although the measure of agreement is even worse here, suggesting minimal agreement between the two devices.