PREDICTORS OF KNEE FUNCTIONAL JOINT STABILITY IN UNINJURED PHYSICALLY ACTIVE ADULTS

by

Nicholas Charles Clark

BEd in Physical Education, University of Greenwich, United Kingdom, 1996

BSc in Physiotherapy, University of East London, United Kingdom, 1999

MSc in Manual Therapy, University College London, United Kingdom, 2002

Post-Graduate Diploma in Clinical Biomechanics, Staffordshire University, United Kingdom, 2007

Submitted to the Graduate Faculty of the

School of Health and Rehabilitation Sciences in partial fulfillment of

the requirements for the degree of

Doctor of Philosophy

University of Pittsburgh

2014

UNIVERSITY OF PITTSBURGH

SCHOOL OF HEALTH AND REHABILITATION SCIENCES

This dissertation was presented

by

Nicholas Charles Clark

It was defended on

March 28, 2014

and approved by

Scott M. Lephart, PhD, ATC. Department of Sports Medicine and Nutrition

John P. Abt, PhD, ATC. Department of Sports Medicine and Nutrition

Mita Lovalekar, MBBS, PhD, MPH. Department of Sports Medicine and Nutrition

David A. Stone, MD. Department of Orthopaedic Surgery

Dissertation Advisor: Timothy C. Sell, PhD, PT. Department of Sports Medicine and Nutrition

PREDICTORS OF KNEE FUNCTIONAL JOINT STABILITY IN UNINJURED PHYSICALLY ACTIVE ADULTS

Nicholas Charles Clark, PhD, PT, CSCS

University of Pittsburgh, 2014

Noncontact knee injuries are a major problem for male and female agility sports athletes. These injuries commonly manifest with a valgus collapse that implicates failure of mechanical and/or sensorimotor mechanisms in maintaining knee functional joint stability (FJS). Previous studies have elucidated the role of some mechanical and sensorimotor characteristics in knee FJS. The contributions of active joint position sense (AJPS) and time-to-peak torque (TTPT) have not been investigated. Therefore, the current evidence-base is incomplete and noncontact knee injury control programs may not be as effective as could be. Identifying the role of AJPS and TTPT in knee FJS will deliver new data that potentially assists design of more effective noncontact knee injury control programs. The purpose of this study was to determine how gender, mechanical joint stability, and selected sensorimotor characteristics predict knee FJS. Two analyses were performed, each with a specific operational definition of knee FJS: 1. adapted crossover hop for distance (ACHD); 2. single-leg stop-jump (SLSJ) total knee valgus displacement.

Thirty-four subjects participated (male (M) 18; female (F) 16; age 24.1 ± 3.5 years; height 171.8 ± 9.6cm; mass 70.6 ± 12.2kg). The dominant leg was tested. The ACHD analysis included: ACHD (cm), gender (M/F), prone knee extension AJPS (motion analysis system; °), anterior tibial displacement (ATD; mm), and isokinetic hamstrings TTPT ($240°\cdot sec^{-1}$; msec). The SLSJ analysis included: SLSJ valgus/varus displacement (motion analysis system; °), gender, AJPS, ATD, SLSJ medial hamstrings feedforward and feedback muscle activation (surface electromyography; % maximum voluntary isometric contraction × sec), and TTPT. Multiple linear regression was performed.

For the ACHD analysis, gender and TTPT contributed to a model that predicted ACHD performance ($R^2 = 0.60$, $P = 0.00$). For the SLSJ analysis, 56% of subjects demonstrated varus displacement and valgus/varus raw data and final equation residuals demonstrated a non-normal distribution.

Gender and hamstrings TTPT should be considered in noncontact knee injury control programs evaluated by single-leg hop tests. Future multivariate studies should consider new knee proprioception tests and employ additional functional tasks to identify clinically important knee valgus displacement.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

PREFACE

There are several acknowledgements I would like to make. This dissertation would not have been completed without the help and support of many people.

To begin, to Dr Scott Lephart; thank you for our scholarly discussions, your advice, and your encouragement since our first meeting in 2002, and for later giving me further opportunity and encouragement over many years to undertake my Doctoral degree at the University of Pittsburgh; it took me a while, and I made it to the NMRL in the end.

To Dr Timothy Sell; thank you for your focus, direction, and counsel throughout this process, wherever you may have been in the country, and whenever I was out of the country; there have been particularly difficult times for me over the past 12 months, and you have kept me on course and been a continuous source of support and encouragement to help me cross the finish line.

To Dr John Abt, Dr Mita Lovalekar, and Dr David Stone; thank you all for being members of my Dissertation Committee, and for your comments, attention to detail, and advice throughout this process; you have all guided me to a place where I feel accomplished and proud of the work I have done.

To Susan Casino and Rob Kornosky; thank you for your perpetual juggling of computer systems, paperwork, emails, and telephone calls; you unselfishly did more than you had to and helped keep me organized; thank you for freeing me up from some administrative matters and giving me extra time to get my hands dirty in the lab.

To the NMRL Graduate Student Researchers and MS Sports Medicine students; thank you for being outstanding colleagues, for giving me the space to collect data, for assisting with setting up equipment, and for giving your time and effort during pilot and reliability testing; I would not have been able to collect data for this dissertation in a timely manner without your willingness and generosity.

To Dr Jonathan Akins, Nicholas Heebner, Matthew Darnell, and Paul Whitehead; gentlemen, you have assisted and supported me with hours of your expertise, time, and effort, and I simply would not have been able to complete this dissertation without your help; thank you for your professionalism and your banter… and all despite the “language barrier”…

To my parents, Noel and Christine Clark; Dad, Mum, you are both missed; thank you for your love and guidance; for giving me the past opportunities that have led me to this present achievement and that now, even in your absence, give me opportunities for my future.

Finally, to my partner, Marianna Ladas; thank you for your love, your understanding, and your constant support, wherever and whenever we might be; you are my inspiration and my strength; I am grateful for You, My Lady.

1.0 INTRODUCTION

Team sports such as basketball, soccer, rugby union, and handball are played by millions of male and female athletes in hundreds of countries.[111, 112, 177, 179] These agility-biased sports require players to advance into another team's territory while maintaining possession of a ball and avoiding opponents' aggressive attempts at interception. Due to the multi-directional and close-quarters nature of these team-based athletic contests, musculoskeletal injuries can occur to all parts of the body.[164] The lower limb accounts for more than 50% of all injuries with the knee being one of the most commonly injured anatomical sites.[6, 7, 78, 164] Traumatic knee injury causes some of the greatest time lost from full athletic participation when compared to other bodily injuries in the same sport,[6, 7, 95] and can result in major academic, occupational, emotional, and financial problems for the individual athlete and society as a whole.[122, 140, 205, 354] As such, traumatic knee injuries are a major burden for the team sport athlete and effective knee injury prevention and rehabilitation strategies are needed.

Traumatic knee injuries occur in a single, clearly defined event,[287, 360] and are divided into "contact" and "noncontact" injuries. A contact injury is defined as when there is body or limb contact with an opponent or external object and typically occurs in tackling situations in team sports.[109, 264, 286] A noncontact injury is defined as when there is no body or limb contact with an opponent or external object and typically occurs during abrupt deceleration maneuvers such as landing from a jump or cutting to suddenly change direction when running.[10, 38, 208]

Noncontact knee injuries most commonly involve a sudden valgus collapse[10, 38, 208] which is a direct manifestation of a loss of knee joint stability. Joint stability is defined as the ability of a joint to remain in or promptly return to proper alignment and functional position through the equalization of forces and balancing of internal and external moments,[308] and is the final product of non-contractile tissue (mechanical) integrity and efficient sensorimotor control mechanisms (e.g. proprioception, neuromuscular control).[185, 308, 309] A noncontact valgus collapse of the knee implicates failure of mechanical integrity and/or sensorimotor control mechanisms in maintaining knee joint stability.

In order to prevent noncontact knee injuries, or optimally rehabilitate athletes with noncontact knee injuries, it is necessary to know which mechanical and sensorimotor control characteristics most contribute to knee joint stability during athletic maneuvers. Past research has attempted to identify strong and significant predictors of knee joint stability using both bivariate correlation and multivariate regression study designs in uninjured and injured knees.[41, 103, 221, 315, 365] A consistent finding of such bivariate and multivariate studies is that strong and significant mechanical and/or sensorimotor predictors of knee joint stability during highly dynamic tasks have yet to be identified.[70, 115, 138] Therefore, in order to design effective and efficient noncontact knee injury prevention and rehabilitation programs for team sports athletes it is necessary to perform further research aimed at identifying which mechanical and/or sensorimotor characteristics, or combinations of characteristics, most contribute to knee joint stability. If the identified mechanical and/or sensorimotor characteristics are modifiable with clinical interventions, such research will assist clinicians with the prioritization of intervention techniques for noncontact knee injury prevention and rehabilitation programs.

1.1 EPIDEMIOLOGY AND MECHANISM OF NONCONTACT KNEE INJURY IN AGILITY-BIASED TEAM SPORTS

1.1.1 Epidemiology of Noncontact Knee Injury

Noncontact knee injuries are common in male and female athletes participating in agility-biased sports such as basketball, soccer, rugby union, and handball.[6, 7, 46, 47, 95, 96, 270] A knee "internal derangement" (e.g. anterior cruciate ligament (ACL)/medial collateral ligament (MCL)/meniscal tear)[94] consistently accounts for large proportions of all severe knee injuries.[6, 7, 46, 47, 95, 96, 270] More than two thirds of all ACL injuries in agility-biased team sports occur in a noncontact situation.[5, 38, 264] Depending on the year, noncontact ACL injury has represented up to 73% to 100% of all basketball and soccer ACL injuries across a 13 year surveillance period.[5] Of the noncontact knee injuries reported in the literature, the ACL, MCL, and meniscus are the most frequently injured anatomical structures.[15, 78, 242] Anterior cruciate ligament, MCL, and meniscal injuries are consistently some of the most severe injuries in agility-biased sports incurring the greatest time lost from full athletic participation[6, 7, 78, 95, 96] and, as such, are a major problem for the team sports athlete.

1.1.2 Mechanism of Noncontact Knee Injury

The mechanism of noncontact knee injury in team sports athletes typically appears to be a sudden progressive valgus collapse (i.e. progressive increase in valgus displacement) of the knee during abrupt deceleration maneuvers such as landing from a jump or cutting to suddenly change direction when running.[10, 38, 40, 208, 368] During deceleration and change-of-direction maneuvers, knee valgus collapse occurs very soon after initial contact in the early part of stance phase.[40, 208, 286] Knee valgus collapse has profound implications for male and female knee injury prevention and rehabilitation programs since cadaver and biomechanical modeling studies have demonstrated that multiplanar combined knee movements that are involved in a noncontact valgus collapse (knee flexion, knee valgus, anterior tibial displacement (ATD), tibial internal rotation) are capable of imposing potentially injurious tensile loads on the ACL and MCL.[33, 128, 245, 348] Excessive knee valgus displacement can also impose extreme compressive loads on the lateral tibiofemoral joint, threatening injury to the lateral tibial and femoral articular surfaces and lateral meniscus.[193, 329, 382] A noncontact valgus collapse of the knee has the potential to simultaneously injure the ACL, MCL, and lateral meniscus, and is a direct manifestation of loss of knee joint stability.

1.2 CONSEQUENCES OF NONCONTACT KNEE INJURY

Noncontact ACL, MCL, and meniscal injuries consistently result in the most extensive time loss from full athletic participation when compared to other knee injuries.[6, 7, 95] These knee injuries result in substantial disruption to occupational commitments and academic studies, and can threaten loss of academic scholarships.[122, 355, 372] The treatment costs for traumatic knee injuries are some of the highest of all sports injuries.[77, 84, 199] In the United States (U.S.), ACL injury costs are estimated at approaching one to two billion dollars per year for acute healthcare alone.[141, 145] In Europe, mean ACL and meniscal injury acute healthcare costs are two of the most expensive of all knee injuries.[84] These cost estimates are only for acute healthcare, they do not include potential later life healthcare costs for traumatic knee injuries that progress to secondary osteoarthrosis. Psychological function can be affected by knee injury. Fear of return-to-sport can be a significant impairment for some athletes after ACL injury.[66, 211, 318] For others, disabling psychological after-effects of injury can include severe depression and even the risk of suicide.[354] Acute knee ligament injuries can result in early retirement from sport, even after ligament reconstruction surgery.[80, 205, 282] Moreover, for those that suffer a clinically significant knee ligament and/or meniscal injury it is almost inevitable that they will experience a premature onset and more rapid progression of post-injury secondary knee osteoarthrosis whether or not reparative surgery is performed.[131, 234, 383]

1.3 JOINT STABILITY

1.3.1 Joint Stability Defined

Joint stability is defined as the ability of a joint to remain in or promptly return to proper alignment and functional position through the equalization of forces and balancing of internal and external moments.[308] Maintaining proper alignment and functional position of the single-joint system is critical for normal human movement, optimal athletic performance, acute joint injury prevention, attenuation of repetitive re-injury, deterring the onset and progression of post-injury secondary osteoarthrosis, and prevention of periarticular peripheral nerve injury.[106, 172, 291, 308] For the single-joint system to successfully achieve the outcomes just described, optimal joint stability is composed of mechanical joint stability (static stability) and functional joint stability (dynamic stability).[43, 185, 280]

1.3.2 Mechanical Joint Stability

Mechanical joint stability refers to joint stability as the result of non-contractile tissues that give a joint its unique shape and structure.[185, 280, 308] These non-contractile joint tissues are termed the "static restraints" and include the bones, capsule, synovium, ligaments, hyaline cartilage, and intra-articular accessory structures (e.g. menisci).[185, 280, 308] Additional factors that contribute to mechanical joint stability are intra-articular pressure due to fluid volume[110, 271] and increased joint friction secondary to joint compression.[167, 246, 370] The combination of intact non-contractile tissues, normal intra-articular pressure, and joint compression result in ideal mechanical joint stability and directly contribute to optimal functional joint stability.

1.3.3 Functional Joint Stability

Functional joint stability refers to joint stability during limb and whole body movements where there is an absence of apprehension, pain, or "giving way" (i.e. sudden joint collapse) during physical activities.[185, 280, 308] In addition to the non-contractile tissues that contribute to mechanical joint stability, essential components of functional joint stability are the skeletal muscles which are termed the "dynamic restraints".[43, 308, 363] The dynamic restraints elicit functional joint stability as a result of feedforward and feedback neuromuscular control which is mediated and preceded by proprioceptive input to the central nervous system (CNS).[43, 220, 363] Knee functional joint stability can be considered the final product of mechanical joint stability, proprioception, feedforward neuromuscular control, and feedback neuromuscular control acting in conjunction with dynamic balance, agility, and an athlete's confidence.[19, 70, 115, 185, 280] If any of the mechanical or sensorimotor control characteristics just described are significantly impaired, joint instability can result. Joint instability refers to functional limitation as a result of specific symptoms and signs that can include pain, a sensation of joint “weakness”, and/or sudden episodes of a joint giving way.[43, 123, 124, 280, 363] A noncontact valgus collapse of the knee is an example of sudden knee joint instability and loss of control of knee joint alignment, and implicates impairment of knee proprioception and/or neuromuscular control.

1.4 PROPRIOCEPTION

1.4.1 Proprioception Defined

Proprioception is historically and classically defined as the sense of position and movement of the joints and limbs, which correspond to joint position sense (JPS) and kinesthesia, respectively.[249, 308, 319] More recently, proprioception has been defined as including the sense of tension/resistance to movement, which is designated force sense.[308, 310, 362] Therefore, proprioception is typically defined as being composed of JPS, kinesthesia, and force sense,[249, 308, 310, 319] which are the result of afferent information generated by mechanoreceptors in the peripheral areas of the body for the purpose of maintaining local joint stability and overall postural control.[139, 223, 308] As such, JPS, kinesthesia, and force sense are critical in contributing to normal human movement and knee functional joint stability.

1.4.2 Role of Proprioception in Knee Functional Joint Stability

Proprioception is the sensory component of sensorimotor control where sensorimotor control is defined as the control of local joint stability, posture, and whole body movement.[133, 223, 350] As such, before effective motor output can be executed for the purposes of maintaining functional joint stability, accurate sensory input (proprioception) must be received by the CNS.[132-134, 319] Proprioceptive input to the CNS modifies motor output at all three levels of the CNS (i.e. spinal cord, brain stem, cerebral cortex) via the local neurocircuitry and ascending systems in the spinal cord and, therefore, has a profound effect on stimulation of the upper and lower motor neurons that form descending tracts which ultimately stimulate extrafusal and intrafusal muscle fibers via the alpha (α) and gamma (γ) motor neurons, respectively.[132, 133, 139, 225, 309] Thus, proprioception directly mediates efferent (motor) responses throughout the CNS for the purposes of maintaining knee functional joint stability, where these efferent responses are specifically termed neuromuscular control.[43, 223, 363]

1.5 NEUROMUSCULAR CONTROL

1.5.1 Neuromuscular Control Defined

Neuromuscular control is the motor component of sensorimotor control and is defined as activation of the dynamic restraints in preparation for and in response to joint motion and loading for the purpose of maintaining and restoring functional joint stability.[308, 309] In essence, neuromuscular control is the efferent (motor) response to an afferent (sensory) signal concerning joint stability,[43, 225, 226] and is proprioceptively-mediated activation of the dynamic restraints in order to stress shield non-contractile tissues from potentially injurious forces and facilitate ideal arthrokinematics during the execution of specific movement patterns.[75, 225, 308] Thus, neuromuscular control manifests as the active restraint of excessive joint motion, the coordinated dampening of joint loads, and the facilitation of efficient movement patterns.[74, 223, 309] To achieve the goals just outlined, neuromuscular control is composed of feedforward and feedback neuromuscular control.

1.5.2 Feedforward Neuromuscular Control

Feedforward neuromuscular control is preparatory activation of and force generation by the dynamic restraints before the onset of afferent stimuli signaling joint loading and/or perturbation.[133, 223, 363] In order to acquire a feedforward motor strategy that preprograms skeletal muscle before joint loading and/or perturbation, previous experience of the physical activity in question and the sensory (proprioceptive) stimuli it generates must have occurred.[133, 134, 223] Therefore, proprioceptive feedback from previous experience (e.g. training) is used to modify feedforward motor programs stored in supraspinal centers,[133, 135, 334] whereby preactivation of the skeletal muscles increases muscle stiffness resulting in greater sensitivity for and reaction to unanticipated single-joint loading and/or perturbation as well as whole body postural disequilibrium.[133, 225, 363]

1.5.3 Feedback Neuromuscular Control

Feedback neuromuscular control is an almost instantaneous ‘at-that-moment-in-time’ motor response to afferent information.[74, 225, 308] With specific regard to functional joint stability, feedback neuromuscular control is reactive activation of and force generation by the dynamic restraints after the onset of afferent stimuli signaling joint loading and/or perturbation.[74, 225, 308] The electromechanical delay (EMD) and rate of force development (RFD) are important components of reactive force generation.[74, 175, 225] The EMD is the timeframe between the onset of reactive muscle activity and the onset of measurable force.[29, 190, 392] The RFD is the timeframe between the onset of measurable force and the achievement of a defined quantity of force.[29, 149, 190] Isokinetic time-to-peak torque (TTPT) is another variable that represents the ability to rapidly and dynamically generate torque[60] and has frequently been employed as a measure of knee feedback neuromuscular control force generating characteristics in the sports medicine literature.[320, 375, 395] Shorter TTPT timeframes represent faster reactive force generation and the potential for more rapid neutralization of post-perturbation joint displacements and, therefore, are highly desirable for enhancing and optimizing feedback neuromuscular control of knee functional joint stability.[176, 395, 397] Thus, feedback neuromuscular control is a critical component of reflex joint stabilization for maintaining knee functional joint stability.[43, 223, 362]

1.6 MECHANICAL AND SENSORIMOTOR CHARACTERISTICS RELATED TO KNEE FUNCTIONAL JOINT STABILITY

1.6.1 Knee Functional Joint Stability Defined

There is no universally agreed "gold standard" for operationally defining and/or measuring knee functional joint stability. For the purposes of clinical research and laboratory studies knee functional joint stability has historically been operationally defined using a variety of methods such as single-leg hop tests,[4, 20, 104, 277, 365] double-leg agility-biased tests (e.g. carioca maneuver),[221, 227] laboratory-based kinematic and kinetic analyses of single- and double-leg functional tasks,[2, 31, 159, 218, 341] and patient self-report questionnaires.[41, 147, 154, 201, 260] Sophisticated laboratory-based kinematic and kinetic equipment is not readily available to the clinician and so single-leg hop tests are popular for defining knee functional joint stability.[19, 70, 115, 232, 233] Single-leg hop tests have a proven association with clinical outcomes after knee ligament injury as well as a predictive ability to identify those who will successfully regain knee functional joint stability after injury.[4, 103, 104, 147, 154, 170] Therefore, it is recommended that single-leg hop tests are routinely employed in all aspects of knee injury control decision-making.[104, 232, 233]

1.6.2 Mechanical Characteristics and Knee Functional Joint Stability

Mechanical knee stability has commonly been measured using a knee arthrometer.[3, 116, 221] Several research groups have employed a knee arthrometer to quantify, for example, ATD in order to make a determination regarding integrity of the ACL relative to knee mechanical joint stability and functional joint stability.[103, 221, 336] In such instances, knee functional joint stability has been operationally defined in a clinical context using single-leg hop tests, agility running tests, and/or subject self-report using questionnaires.[103, 201, 221, 277, 336, 388] A consistent finding from correlation work in both uninjured and injured athletes is that knee mechanical joint stability defined by the magnitude of ATD is only weakly/moderately related to knee functional joint stability.[103, 201, 221, 313, 336, 388] Multiple regression studies have also found that knee mechanical joint stability does not predict knee functional joint stability in injured athletes.[105, 170]

1.6.3 Proprioception Characteristics and Knee Functional Joint Stability

According to Riemann and Lephart[310] proprioception measurements represent the acquisition and transmission of mechanical stimuli by peripheral afferents. Knee proprioception has commonly been measured in uninjured and injured athletes using threshold to detection of passive motion (TTDPM) as a specific test of knee kinesthesia,[3, 41, 42, 320, 325, 326] with the premise that TTDPM biases capsuloligamentous proprioceptors because muscle tissue is relatively relaxed and inactive (passive).[310, 325, 352] In such instances, knee functional joint stability has again been operationally defined using single-leg hop tests and/or subject self-reports.[41, 42, 59, 215] A consistent finding from correlation studies is that passive measures of knee proprioception are also only weakly/moderately related to knee functional joint stability.[3, 41, 42, 59, 125, 126] Multiple regression analysis also demonstrates that passive measures of proprioception do not predict knee functional joint stability in previously injured physically active individuals.[41] Based on such consistent research findings, it has recently been stated that passive measures of knee proprioception such as TTDPM yield little clinical relevance or practical utility, and new more valid tests of knee proprioception need to be developed.[138]

1.6.4 Neuromuscular Control Characteristics and Knee Functional Joint Stability

According to Riemann and Lephart[310] neuromuscular control measurements represent aspects of efferent transmission and include electromyography (EMG), muscle performance, kinetic, and kinematic characteristics. Electromyography studies that have measured hamstring feedforward neuromuscular control (e.g. pre-landing muscle activation) within multivariate regression experimental designs have reported non-significant associations with functional knee stability defined peak knee valgus angles during single-leg landing tasks.[53, 290] Similarly, EMG studies that have measured hamstring feedback neuromuscular control (e.g. post-perturbation reflex latency) within bivariate correlation paradigms have reported non-significant correlations, or only significant weak/moderate correlations, with knee functional joint stability defined by single-leg hop tests and questionnaires.[25, 27, 71] Dynamometry studies employing absolute/relative strength variables repeatedly identify non-significant or significant weak/moderate associations between quadriceps and hamstring muscle performance and knee functional joint stability in uninjured and injured subjects.[41, 105, 114, 206, 221, 277, 294, 336, 365, 388] Kinetic and kinematic studies sampling peak vertical ground reaction forces and peak knee valgus angles collected during a double-leg drop vertical jump report that such variables are only moderately related in uninjured athletes.[159]

1.6.5 Clinical Implications of Past Research

Male and female athletes with post-trauma mechanical knee instability defined by, for example, increased ATD after ACL injury can return to unrestricted participation in agility-biased team sports despite being ACL-deficient (ACL-D).[80, 227, 259] Many ACL-D athletes safely participate in research studies involving single-leg hop tests and double-leg agility-biased maneuvers as operational definitions of knee functional joint stability.[41, 42, 103, 147, 227] Other athletes with ACL-D knees have adequate knee functional joint stability during unrestricted agility-biased sports as reported via questionnaire surveys.[41, 147, 154, 201, 260] Evidence of adequate knee functional joint stability has also emerged for the PCL-deficient (PCL-D) knee.[116, 238, 244, 346, 347] Collectively, these works indicate an athlete's ability to compensate for the loss of a major knee ligament (static restraint) with other mechanisms, supporting the notion that knee functional joint stability is in fact a cumulative effect of multiple mechanical and sensorimotor characteristics.[19, 70, 115]

Multiple mechanical and sensorimotor characteristics are significantly correlated with various clinical, laboratory, and subjective operational definitions of knee functional joint stability, but the strength and clinical relevance of such correlations is questionable. Regression analyses using selected mechanical and sensorimotor characteristics as the predictor variables are inconsistent with regard to conclusively identifying strong predictors of knee functional joint stability defined by single-leg hop tests, questionnaires, and knee valgus angles in uninjured and injured athletes. Therefore, the major clinical implication of this past research is that it remains unknown which mechanical and/or sensorimotor characteristics are most strongly related to, or predict the ability to, maintain knee functional joint stability and participate in unrestricted agility-biased team sports.

1.7 DEFINITION OF THE PROBLEM

Noncontact knee injuries are a major problem for male and female agility-biased team sports athletes that commonly manifest as a sudden valgus collapse of the knee and frequently result in ACL, MCL, and/or meniscal injury. A sudden noncontact valgus collapse of the knee implicates failure of mechanical and/or sensorimotor characteristics in maintaining knee functional joint stability. Previous correlation and regression studies have made a valuable contribution to the literature in that they have elucidated the role of selected mechanical (e.g. ATD) and sensorimotor characteristics (e.g. TTDPM, hamstring feedforward/feedback neuromuscular control) “local” to the knee in contributing to knee functional joint stability in uninjured and injured athletes. This past work has enabled clinicians to begin designing effective knee injury prevention and rehabilitation programs. The contributions of active joint position sense (AJPS) (as a measure of proprioception) and TTPT (as a measure of feedback neuromuscular control force generating characteristics) to local knee functional joint stability have not yet been investigated. Therefore, the current evidence-base is incomplete and knee injury risk factor analyses, injury prevention programs, and injury rehabilitation programs may not yet be as effective or efficient as could be. Identifying the potential role of AJPS and TTPT in knee functional joint stability will add valuable information to the literature. This information will contribute to a more complete picture of which sensorimotor characteristics most contribute to local knee functional joint stability and deliver new data that expands the existing evidence-base to potentially assist clinicians with the design and development of more effective and efficient noncontact knee injury prevention, injury rehabilitation, and performance optimization programs.

1.8 PURPOSE

The purpose of this study was to determine the extent to which gender (male (0)/female (1)), knee anterior tibial displacement (millimeters (mm)), prone knee extension active joint position sense (absolute error (AE); °), medial hamstrings preparatory muscle activity integrated EMG (iEMG; (percentage maximum voluntary isometric contraction (MVIC) multiplied by second (%MVIC × sec)), medial hamstrings reactive muscle activity iEMG (%MVIC × sec), and knee flexion time-to-peak torque (milliseconds (msec)) predicted knee functional joint stability. Two multiple regression models were examined with a specific operational definition of knee functional joint stability as the outcome variable for each: 1. single-leg hop distance (cm) for the adapted crossover hop for distance test; 2. total knee valgus displacement (°) for the single-leg stop-jump test.

1.9 SPECIFIC AIMS AND HYPOTHESES

Specific Aim 1: To determine the ability of gender (male (0)/female (1)), anterior tibial displacement (mm), prone knee extension active joint position sense absolute error (°), and knee flexion time-to-peak torque (msec) to predict knee functional joint stability defined by the adapted crossover hop for distance single-leg hop distance (cm).

Hypothesis 1: Gender, anterior tibial displacement, prone knee extension active joint position sense absolute error, and knee flexion time-to-peak torque would significantly predict adapted crossover hop for distance single-leg hop distance. As anterior tibial displacement, prone knee extension active joint position sense absolute error, and knee flexion time-to-peak torque all decrease then adapted crossover hop for distance single-leg hop distance would increase. Also, males will hop further than females.

Specific Aim 2: To determine the ability of gender (male (0)/female (1)), anterior tibial displacement (mm), prone knee extension active joint position sense absolute error (°), medial hamstrings preparatory muscle activity iEMG (%MVIC × sec), medial hamstrings reactive muscle activity iEMG (%MVIC × sec), and knee flexion time-to-peak torque (msec) to predict knee functional joint stability defined by single-leg stop-jump total knee valgus displacement (°).

Hypothesis 2: Gender, anterior tibial displacement, prone knee extension active joint position sense absolute error, medial hamstrings preparatory muscle activity iEMG, medial hamstrings reactive muscle activity iEMG, and knee flexion time-to-peak torque would significantly predict single-leg stop-jump total knee valgus displacement. As anterior tibial displacement, prone knee extension active joint position sense absolute error, and knee flexion time-to-peak torque all decrease, and medial hamstrings preparatory and reactive muscle activity iEMG both increase, then total knee valgus displacement would decrease. Also, males would have less total knee valgus displacement than females.

1.10 STUDY SIGNIFICANCE

The identification of mechanical and/or sensorimotor characteristics that significantly predict knee functional joint stability will present the researcher and clinician with potential intervention priorities for knee injury prevention and rehabilitation programs. The identified characteristics could then be targeted with training methods known to positively affect the characteristics' functional properties.[339] For the researcher, the identified characteristics could be incorporated into prospective research aimed at identifying potential modifiable injury risk factors and predictors of optimal performance:[339] specifically, noncontact ACL, MCL, and meniscal injury prevention and knee performance optimization in agility-biased team sports. For the clinician, the identified characteristics could be emphasized in noncontact ACL, MCL, and meniscal injury rehabilitation programs in a way that is intended to increase the efficacy of treatment interventions and enhance post-injury outcomes for the agility-biased team sports athlete.[221] According to Rivara,[314] injury control is composed of three phases: injury prevention, acute care, and injury rehabilitation. Thus, this study will have the potential to significantly contribute to the injury prevention and injury rehabilitation phases of noncontact knee injury control.

2.0 REVIEW OF LITERATURE

This review of literature will focus on selected basic sciences, laboratory research, and clinical research specific to noncontact knee injury in agility-biased team sports. Contact and noncontact knee injury will be operationally defined. The injury epidemiology, mechanism of injury, consequences of injury, joint stability, proprioception, and neuromuscular control pertaining to noncontact knee injury will be reviewed. Following this, methodological considerations for this study will be outlined.

2.1 CONTACT AND NONCONTACT KNEE INJURY DEFINED

For any commentary on knee injury to be fully understood, operational definitions of knee injury mechanisms are fundamentally important. The literature is, however, inconsistent with regard to the definition of "contact" and "noncontact" knee injury. Agel et al.[5] define a contact knee injury as when there is contact with another athlete or piece of equipment, and noncontact knee injury as when there is no contact with another athlete. Hewett et al.[159] define a noncontact knee injury as when there is no direct blow to the knee, although there can be "minimal contact" with another athlete with another part of the body (e.g. shoulder-to-shoulder contact during a basketball rebound).[40] Krosshaug et al.[208] classify a contact knee injury as involving a direct blow to the knee itself, any foot-to-foot contact with another athlete, and any collision, pushing, or holding with other athletes. Mountcastle et al.[264] define a contact knee injury as when there is contact to the body, and noncontact knee injury as when there is no contact with another athlete. Olsen et al.[286] define a contact knee injury as including all types of contact whether it is a direct blow to the injured athlete's lower limb or indirect contact with any other part of the body. Following these inconsistent operational definitions, Marshall et al.[247] present a schema for defining knee injury mechanisms: "direct contact" is when there is a direct blow to the knee; "indirect contact" is when there is no direct blow to the knee but there is still some form of bodily contact with another athlete; and "noncontact" is when there is no contact with another athlete or an external object. For this research study, a "contact" knee injury is operationally defined as when there is any body or limb contact with another athlete or external object at the moment of injury. A "noncontact" knee injury is operationally defined as when there is no body or limb contact with another athlete or external object at the moment of injury.

2.2 EPIDEMIOLOGY OF NONCONTACT KNEE INJURY IN AGILITY-BIASED TEAM SPORTS

Epidemiology is the study of the distribution, frequency, and severity of disease and/or injury.[298] Knowledge of the scope, magnitude, and severity of an injury is important for prioritizing injury prevention and rehabilitation interventions and for the effective allocation of human and material healthcare resources. Noncontact knee injuries frequently occur in male and female athletes participating in agility-biased team sports such as basketball, soccer, rugby union, and handball.[6, 7, 46, 47, 78, 95, 96, 270] According to Dick et al.[94] and the National Collegiate Athletic Association (NCAA) noncontact knee injuries can manifest as a knee "internal derangement" which is operationally defined as an ACL, MCL, and/or meniscal tear. In college basketball the incidence rate of male and female knee internal derangement is 0.26-0.66 per 1,000 athlete-exposures and 0.37-1.22 per 1,000 athlete-exposures, respectively.[7, 95] Of these injuries, noncontact knee internal derangements account for 17.8% to 21.2% and 26.1% to 41.9% of all severe knee injuries in male and female players, respectively.[7, 95] In college soccer, the incidence rate of male and female knee internal derangement is 0.33-2.07 per 1,000 athlete-exposures and 0.40-2.61 per 1,000 athlete-exposures, respectively.[6, 96] Of these injuries, noncontact knee internal derangements account for 23.5% and 25.5% of all severe knee injuries in male and female players, respectively.[6, 96] In professional rugby union, the incidence rate of male ACL injury is 0.01-0.42 per 1,000 player-hours, MCL injury is 0.04-3.10 per 1,000 player-hours, and meniscal injury is 0.03-2.20 per 1,000 player-hours.[46, 47, 78] Noncontact knee injuries account for 22% to 39% of all severe ACL, MCL, and meniscal injuries in male rugby union players.[46, 47, 78] In elite handball, the incidence rate of male and female cruciate ligament injuries is 0.27-0.54 per 1,000 player-hours and 0.72-1.62 per 1,000 player-hours, respectively.[270] Noncontact knee injury accounted for 95% of all severe cruciate ligament injuries in these male and female players.[270]

More than two-thirds of all ACL injuries are consistently reported as occurring in a noncontact situation.[5, 38, 264] Agel et al.[5] report that of all male and female NCAA basketball and soccer ACL injuries over a 13 year surveillance period, more than 66% of ACL injuries were due to a noncontact mechanism of injury. Mountcastle et al.[264] report that of all male and female West Point Military Academy students participating in basketball, soccer, and handball over a nine year surveillance timeframe, a noncontact mechanism of injury accounted for 67.2% of all ACL injuries in males and 89.4% of all ACL injuries in females. Of all noncontact knee injuries reported in the literature, the ACL, MCL, and meniscus are consistently the most frequently injured anatomical structures for both male and female athletes.[15, 78, 242] Females demonstrate a higher incidence rate of knee internal derangements and a larger proportion of noncontact knee injuries than males for the same agility-biased team sports.[6, 7, 95, 96, 270] Both males and females experience knee internal derangements as a result of noncontact knee injury.[6, 7, 95, 96, 270] Noncontact knee internal derangements are, therefore, a major problem for both male and female agility-biased team sports athletes.

2.3 MECHANISM OF NONCONTACT KNEE INJURY IN AGILITY-BIASED TEAM SPORTS

2.3.1 Noncontact Knee Injury Kinematics

A precise description of the inciting event for an injury gives insight into the movement patterns involved at the moment of injury and the anatomical structures that can be injured as a result of excessive movement in one or more directions. Research methods used to identify the mechanism of noncontact knee injury in male and female team sports athletes have included various types of videotape analyses of actual injury events. Teitz[368] reports basic visual inspection of videotaped ACL injury events in male and female team sports athletes. Videos were slowed down, freeze-frames created for the perceived moment of injury, and a standardized reporting form completed to describe the mechanism of injury including: contact vs. noncontact, activity at the moment of injury (e.g. jump landing, deceleration when running), ground contact (double-leg, single-leg), center of gravity position (e.g. in front of knee, behind knee), and knee alignment (e.g. valgus, varus). A consensus of surgeons’ observations revealed the majority of noncontact ACL injuries occurred when decelerating from running or when landing from a jump, and that at the perceived moment of injury the knee was commonly in less than 30° of knee flexion and a valgus alignment.[368] Boden et al.[40] performed slow-motion and freeze-frame videotape analyses of the moment of noncontact ACL injury in male and female team sports athletes performing deceleration or landing maneuvers. Hip, knee, and ankle kinematics were viewed at 30 Hertz (Hz) and freeze-frame joint angles were measured using a commercially available digital image processing program. Results demonstrated that a progressive valgus collapse of the knee (i.e. progressive increase in valgus displacement) was experienced by both male and female athletes very soon after initial contact when the knee was in relatively small amounts of flexion. Krosshaug et al.[208] also undertook slow-motion and freeze-frame videotape analyses of the moment of noncontact ACL injury in male and female team sports athletes. Hip and knee kinematics were viewed at 60 Hz, freeze-frame joint angles were visually estimated by the observers, and a standardized reporting form completed to identify specific characteristics at the perceived moment of injury (e.g. double- vs. single-leg landing, double- vs. single-leg stopping, foot-width). Observations revealed that the majority of injuries occurred when landing from a jump, with a progressive valgus collapse of the knee demonstrated by both male and female athletes. Olsen et al.[286] performed slow-motion, freeze-frame, and digitally-enhanced videotape analyses of the moment of ACL injury in team sports athletes. Videotapes were slowed, still images created, enlarged, and digitized, and activity categories (e.g. plant-and-cut, landing from a jump) and knee alignment (e.g. valgus, varus) at both foot-strike and the perceived moment of injury recorded on a standardized form. The consistent pattern of injury was a valgus collapse of the knee in small amounts of flexion when cutting to change direction or when single-leg landing from a jump.

Videotape recordings have also been combined with computer modeling techniques to describe the kinematics of noncontact knee injury. Koga et al.[204] performed highly intricate three-dimensional (3D) model-based image-matching (MBIM) reconstructions of noncontact ACL injury events in female basketball and handball players from high-quality television video recordings. Video recordings were slowed to 50 Hz or 60 Hz, a 21-segment 3D skeletal model created and matched to selected anthropometric measurements in each athlete, and the 3D model then overlaid and matched to the videotapes. Results demonstrated that noncontact ACL injuries occurred during a sudden cutting maneuver to change direction when running or when single-leg landing from a jump, and that very soon after initial contact injured knees consistently experienced a progressive collapse involving a combined movement pattern of knee flexion, knee valgus, and tibial internal rotation. Koga et al.[203] employed the same 3D MBIM methodology just outlined to describe the kinematics of noncontact ACL injury in a male professional soccer player. Data showed that noncontact ACL injury occurred when attempting to suddenly stop when running, and that just after initial contact the injured knee experienced a rapid progressive collapse involving the combined movements of knee flexion, knee valgus, ATD, and tibial internal rotation. Krosshaug et al.[209] also used the 3D MBIM technique to describe a noncontact ACL injury in a male basketball player. Sequences showed that the player was injured during a single-leg landing after catching the ball in the air, and that the knee underwent a progressive collapse involving the combined movements of knee flexion, knee valgus, and tibial internal rotation.

The consistent mechanism of noncontact knee injury across males and females appears to be a sudden and progressive valgus collapse of the knee (progressive increase in valgus displacement) during abrupt deceleration maneuvers such as landing from a jump or cutting with a sudden change direction. A noncontact valgus collapse of the knee occurs very soon after initial contact in the early part of stance phase and consistently involves combined movements of knee flexion, knee valgus, ATD, and tibial internal rotation.

2.3.2 Noncontact Knee Injury Kinematics and Tissue Damage

The movement patterns involved at the moment of injury implicate the anatomical structures that can be injured as a result of aberrant joint motion. Noncontact knee valgus collapse displays a rapid and extensive “opening” of the medial tibiofemoral joint.[204] This has profound implications for male and female knee injury prevention and rehabilitation programs since cadaver and biomechanical modeling studies have demonstrated that the combined multiplanar knee movements consistently involved in a noncontact valgus collapse (flexion, valgus, ATD, tibial internal rotation) are capable of imposing potentially injurious tensile loads on the ACL and MCL. Berns et al.[33] used a custom load application system to impose pure (anterior-posterior shear, varus-valgus torque, internal-external rotation torque) and combined (e.g. anterior shear plus valgus torque) loads to human cadaveric knees at different knee flexion angles (0°, 15°, 30°). Strain in the ACL was measured with a liquid mercury strain gauge. Results demonstrated that at 30° knee flexion combined loading states of anterior shear plus valgus torque and anterior shear plus internal rotation torque generated significantly higher ACL strain than anterior shear force alone. Fukuda et al.[128] employed a robotic testing system to apply pure valgus torques to human cadaveric knees at varying degrees of knee flexion (15°, 30°, 45°, 60°). As valgus torques were applied, coupled ATD and tibial internal rotation were measured along with *in situ* ACL forces. Data demonstrated that as valgus torques increased mean ATD and tibial internal rotation also increased at all angles of knee flexion. The *in situ* ACL forces were significantly higher at knee flexion angles from 15° to 45° versus 60°. Markolf et al.[245] used a custom apparatus that facilitated the application of controlled loads (ATD, varus-valgus torque, internal-external rotation torque) in a variety of combinations to human cadaveric knees at different angles of knee flexion (10° hyperextension to 90° flexion). Tensile forces in the ACL were measured under all loading conditions. Results demonstrated that ACL tensile forces were significantly higher at knee flexion angles less than 30° with combined loading conditions of ATD plus internal rotation torque and ATD plus valgus torque versus any single loading condition alone. Shin et al.[348] employed a dynamic 3D simulation model validated alongside previous cadaver and *in vivo* work to study the effects of valgus loading on the ACL and MCL during single-leg landings. Peak strain for the ACL and anterior and deep bundles of the MCL were mathematically modeled. Data showed that peak ACL and MCL strain significantly increased during knee flexion when valgus loads were applied to the knee. Thus, cadaveric and mathematical modeling studies from multiple research groups confirm the kinematics observed during a noncontact knee valgus collapse impose clinically significant loads upon the ACL and MCL.

The excessive knee valgus displacement displayed during a noncontact valgus collapse also displays a rapid and progressive “closing down” of the lateral knee joint.[204] This imposes potentially extreme compressive loads on the lateral compartment of the tibiofemoral joint, threatening injury to the lateral tibial and femoral articular surfaces and lateral meniscus. Kaplan et al.[193] used magnetic resonance imaging (MRI) to catalogue osteochondral injuries associated with acute ACL tears. Occult fractures of the tibia and femur were counted and proportions calculated. Results showed that lateral tibial plateau fractures were present in 100% of knees and that lateral tibial plateau and lateral femoral condyle fractures coexisted in almost 50% of knees.

Sanders et al.[329] reviewed the literature with regard to MRI scans associated with different types of knee trauma including noncontact ACL injury. A consistent finding was that noncontact ACL injuries were associated with a bone contusion pattern involving the lateral tibial plateau and lateral femoral condyle. Viskontas et al.[382] examined MRI scans in 86 athletes with an acute noncontact ACL injury. Scans were examined for the presence of tibial and femoral bone bruises and MCL tears and proportions calculated. Data demonstrated that in addition to an ACL tear, the majority of athletes also sustained a deep bone bruise to the lateral tibial plateau and lateral femoral condyle, and an injury to the MCL. Thus, diagnostic imaging studies from several clinical centers corroborate that the kinematics observed during a noncontact knee valgus collapse impose clinically significant compressive loads on the tissues of the lateral tibiofemoral joint.

2.3.3 Summary

Understanding injury causation is a critical step in identifying how sports injuries occur and developing injury prevention strategies. A noncontact valgus collapse of the knee is characterized by a kinematic pattern that includes combined knee flexion, knee valgus, ATD, and tibial internal rotation. This kinematic pattern is seen in both male and female agility-biased team sports athletes. Combined knee flexion, knee valgus, ATD, and tibial internal rotation threatens the integrity of the ACL, MCL, lateral tibial plateau, lateral femoral condyle, and lateral meniscus. A noncontact valgus collapse of the knee has the potential to simultaneously injure multiple knee tissues and is a direct manifestation of loss of knee joint stability.

2.4 CONSEQUENCES OF NONCONTACT KNEE INJURY

Understanding the consequences of noncontact knee injury is important for fully understanding the short- and long-term impact such an injury has on the individual and society as a whole. This understanding facilitates the development of strategies for the appropriate allocation of resources for noncontact knee injury prevention and rehabilitation programs. Appropriate allocation of resources is essential if the severity, morbidity, and impact of noncontact knee injuries is to be reduced across the lifespan.

2.4.1 Social and Economic Consequences

The severity of a noncontact knee injury is frequently operationally defined as the number of days for which the injured athlete is unable to return to full sports participation, also referred to as "time loss".[78, 94] In basketball,[7, 95] soccer,[6, 96] and rugby union,[78] noncontact knee internal derangements consistently resulted in the most extensive time loss when compared to other knee injuries.

Knee injuries result in substantial disruption to occupational commitments and academic studies, and can threaten loss of academic scholarships.[122, 355, 372] Freedman et al.[122] showed that a significantly larger proportion of students (33%) who elected for ACL-R during a semester did not complete their classwork compared to students (9%) who elected for ACL-R during a break. Trentacosta et al.[372] reported that a major proportion of students (36.4%) who underwent knee surgery during the school year failed an academic test versus students (0%) who underwent surgery during the Summer break.

The cost of medical treatment for traumatic knee injuries is often the highest of all sports injuries.[77, 84, 199] In Scandinavia, de Loes et al.[84] report that the mean medical cost of a cruciate ligament injury (U.S. $2,711.00 - $2,836.00) exceeds that for all other traumatic knee injuries (e.g. patellar dislocation: U.S. $1,023.00 - $1,113.00). In the U.S., individual medical costs for ACL-R have been estimated at $11,500.00,[141] with a nationwide cumulative estimate for all ACL-R surgeries at approximately one billion dollars[145] to two billion dollars[141] per year.

2.4.2 Psychological, Emotional, and Physical Consequences

Psychological and emotional function can be affected by knee injury. Fear of return-to-sport can be a significant impairment for some athletes after ACL injury.[66, 211, 318] Chmielewski et al.[66] investigated the effects of fear of movement/re-injury after ACL-R. A shortened version of the Tampa Scale of Kinesiophobia (TSK), the TSK-11, was administered to three groups of subjects at different time-points post-surgery (less than 90 days, 90 to 180 days, 181 to 372 days). All groups demonstrated levels of fear of movement/re-injury, with a decrease in symptoms being associated with an increase in time from surgery. Kvist et al.[211] also studied the effects of fear of movement/re-injury after ACL-R. A modified version of the TSK was administered to patients three to four years post-surgery. Of the study cohort, 47% had a significantly high score on the TSK and had not returned to their pre-injury level of physical activity. A significant correlation ($r = -0.50$, $P < 0.05$) existed between fear of movement/re-injury and knee-related quality of life. In other work, Smith and Milliner[354] reviewed the literature with regard to depression and risk of suicide after sports injury. The authors concluded that severe depression and suicidal tendencies were possible and existed in elite athletes suffering from a disabling injury that removed them from sports participation.

Acute knee ligament injuries can result in early retirement from sport, even after ligament reconstruction surgery.[80, 205, 281, 282] Daniel et al.[80] reported the effects of ACL injury in four groups of patients (I: mechanically stable, no ACL-R; II: mechanically unstable, no functional limitation; III: ACL-R less than 90 days post-injury; IV: ACL-R more than 90 days post-injury) at a minimum of two years post-injury. Patients were interviewed with regard to the level and number of hours per year of sports participation. At follow-up, approximately 50% of all patients in all groups had had to significantly reduce the level and/or number of hours per year participating in sports relative to their pre-injury status.

For those that suffer a clinically significant knee ligament and/or meniscal injury it is almost inevitable that they will experience a premature onset and more rapid progression of post-injury secondary knee OA whether or not reparative surgery is performed.[131, 234, 383] Lohmander et al.[234] performed a 12 year follow-up on 67 female soccer players who had sustained an ACL injury. Mean age at the time of follow-up was 31 years. Subjects' tibiofemoral and patellofemoral joints were evaluated with weight-bearing radiographs and then graded for the presence of OA. Results demonstrated that more than 50% of the sample fulfilled the study's criteria for radiographic OA. In another study, von Porat et al.[383] carried out a 14 year follow-up on 122 male soccer players who had sustained an ACL injury. Mean age at follow-up was 38 years. Subjects' tibiofemoral joints were examined using weight-bearing radiographs and subsequently graded for the presence of OA. Results showed that 78% of the players fulfilled the study's operational definition for radiographic OA.

2.4.3 Summary

Understanding the consequences of noncontact knee injury is important for the allocation of resources for noncontact knee injury prevention and rehabilitation programs. There are multiple social, economic, psychological, emotional, and physical consequences of knee injury that potentially extend many years beyond the time of actual injury and interfere with quality of life across the lifespan. Effective noncontact knee injury prevention and rehabilitation programs are, therefore, critical for limiting the negative impact of injury on the individual, the healthcare system, and broader society.

2.5 JOINT STABILITY

Several mechanical and sensorimotor characteristics contribute to optimal knee joint stability. An understanding of knee joint stability is necessary to appreciate the relative contribution of each component to optimal knee function and health. This, in turn, identifies which components of knee joint stability may be most important in knee injury prevention, rehabilitation, and performance optimization programs.

Joint stability refers to the ability of a joint to remain in or promptly return to proper alignment and functional position through the equalization of forces and balancing of internal and external moments.[308] Proper alignment and functional position of the single-joint system is critical for normal human movement, optimal athletic performance, acute joint injury prevention, attenuation of repetitive re-injury, deterring the onset and progression of post-injury secondary OA, and prevention of periarticular peripheral nerve injury.[106, 172, 291, 308] Optimal single-joint stability is composed of mechanical joint stability (static stability) and functional joint stability (dynamic stability).[43, 185, 280]

2.5.1 Mechanical Joint Stability

Mechanical joint stability refers to joint stability as the result of non-contractile tissues that give a joint its unique shape and structure.[185, 280, 308] These non-contractile tissues are termed the "static restraints" and include the bones, capsule, synovium, ligaments, hyaline cartilage, and intra-articular accessory structures (e.g. menisci).[185, 280, 308] The knee joint is formed by the tibiofemoral and patellofemoral joints. The tibiofemoral joint is formed by the femoral condyles articulating with the tibial plateau, where the femoral condyles are convex in shape while the tibial plateau is relatively flat.[192, 275] Therefore, the tibiofemoral joint is relatively unstable in all planes of motion due to incongruence of the bony surfaces.[192, 275] The tibiofemoral (knee) joint is highly dependent on capsuloligamentous structures for mechanical stability.[192, 275]

Knee ligaments can function as "primary" or "secondary" restraints according to the direction of joint motion.[56] The ACL provides a mean of 86% of the total restraining force to straight-plane ATD in the intact human knee between 30° and 90° knee flexion, being designated a primary restraint for tibial translation in an anterior direction.[56] The MCL provides a mean of 16% of the total restraint to ATD, being designated a secondary restraint for tibial translation in an anterior direction.[56] For straight-plane valgus motion, the MCL provides a mean of 57% and 78% of total restraint at 5° and 25° knee flexion, respectively, thereby being the primary ligamentous restraint to knee valgus displacement.[148] The ACL and PCL together provide a mean of 15% and 13% of the total restraint to valgus motion at 5° and 25° knee flexion respectively, being classified as a secondary ligamentous restraints to knee valgus displacement.[148]

Other factors also contribute to mechanical stability of the knee. The medial knee joint capsule contributes 8% to 25% of the total restraint to straight-plane valgus motion at 25° and 0° knee flexion, respectively.[148] In the ligament-intact knee at 0° and 30° knee flexion, the menisci do not make a large contribution to limiting anterior or internal rotation displacements of the tibiofemoral joint.[167] In the ACL-D knee, however, the menisci make a significant contribution to limiting ATD and internal rotation displacement of the knee at 0° and 30° knee flexion.[167] Intra-articular pressure due to fluid volume can affect mechanical knee joint stability.[110, 271] Joint compression increases anteroposterior,[167, 246] varus-valgus,[246] and internal-external rotation[167] stability of the knee.

Multiple non-contractile tissues function as static restraints in maintaining mechanical knee joint stability. Considering that the knee joint is relatively incongruent due to the shape of its bony components,[192, 275] and that a noncontact valgus collapse of the knee involves the combined movements of flexion, ATD, valgus, and internal rotation,[203, 204, 209] the mechanical integrity of the ACL and MCL is particularly important in potentially limiting excessive knee valgus displacement and preventing injury. Thorough assessment of the mechanical integrity of the ACL and MCL is clinically important in order to determine the status of the static restraints and make well-reasoned intervention decisions.

2.5.2 Measurement of Knee Mechanical Joint Stability

The mechanical integrity of the ACL and MCL can be estimated using manual (clinical) laxity tests. Commonly recommended clinical laxity tests for the ACL and MCL are the Lachman’s test and valgus stress test (0° and 30° knee flexion), respectively.[236] Both the Lachman’s test and the valgus stress test are qualitatively scored according to the amount of laxity that is perceived to be present by the examiner, with higher scores representing greater laxity.[236] Although commonly used, the performance and results of clinical laxity tests for the knee can be highly variable across even experienced examiners.[279]

Anterior cruciate ligament integrity can also be estimated using, for example, the KT-1000 arthrometer (Figure 1).[253, 303] The KT-1000 has been widely used for describing the integrity of the ACL[80, 81, 303] because ATD is the primary mechanism by which the ACL is loaded.[56] The KT-1000 is recommended on an international level for the clinical objective measurement of ATD as part of a comprehensive test battery intended to fully characterize knee function,[155] and quantitatively measures ATD in millimeters with higher values representing greater ACL laxity (or disruption).[80, 81] There is no equivalent device commercially available for performing knee valgus stress tests and quantitatively measuring knee valgus displacement as an indication of MCL integrity.

To properly and comprehensively characterize knee joint stability measures of knee mechanical joint stability should be performed. Because non-instrumented tests of ATD are subjective in nature, objective tests using, for example, the KT-1000 are preferable for the quantitative measurement of anterior knee laxity. The findings of objective tests of knee mechanical joint stability can then help the analysis and interpretation of findings from other tests focused on evaluating knee functional joint stability.

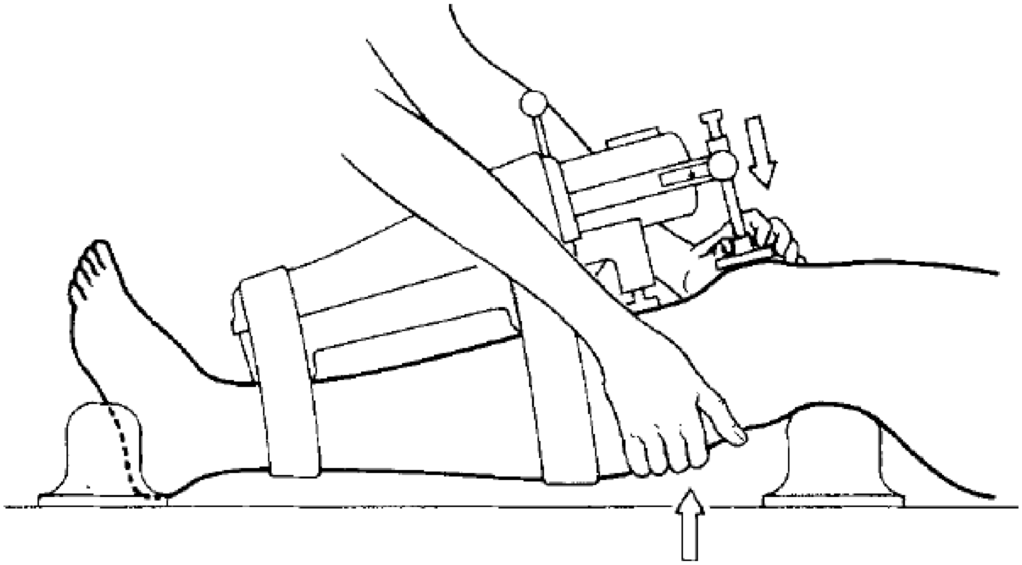

Figure 1. KT-1000 Manual Maximum Test Configuration

From: Rangger et al.[303]

2.5.3 Functional Joint Stability

Functional joint stability refers to joint stability during limb and whole body movements.[308] Other authors have stated functional joint stability exists where there is an absence of apprehension, pain, or “giving way” (i.e. sudden joint collapse) during physical activities.[185] Essential components of functional joint stability are the skeletal muscles which are termed the “dynamic restraints”.[43, 308, 363] The dynamic restraints elicit functional joint stability as a result of feedforward and feedback neuromuscular control which is mediated and preceded by proprioceptive input to the CNS.[43, 220, 363] Functional joint instability refers to functional limitation as a result of specific symptoms and signs that can include pain, a sensation of joint “weakness”, and/or sudden episodes of a joint giving way.[43, 123, 124, 280, 363] A noncontact valgus collapse of the knee is an example of sudden knee functional joint instability and loss of control of knee joint alignment.

Muscles which are capable of restraining excessive joint motion in a specific direction are capable of limiting functional joint instability by maintaining optimal joint alignment during dynamic tasks.[280, 363] Research shows the prime movers of the knee (hamstrings, quadriceps) are able to act as dynamic restraints to limit the combined movements that typically occur with a noncontact valgus collapse, where the hamstrings are specifically capable of limiting ATD and thereby reducing ACL strain.[160, 178, 261] Hirokawa et al.[160] investigated the effects of artificial hamstrings activity on ATD in 12 human knees using a cadaver-radiograph experimental model. Hamstrings loads was superimposed on simulated quadriceps loads in 15° increments from 0° to 120° knee flexion and a lateral radiograph taken to measure ATD. Data showed that hamstrings load decreased ATD at knee flexion angles more than 15°. More et al.[261] studied the effects of simulated hamstrings activity on ATD in 10 ACL-intact and ACL-D human cadaver knees mounted in an Oxford Rig. A linear potentiometer measured ATD at increasing angles of knee flexion (0° to 90°). Results demonstrated that at flexion angles more than 15° the simulated hamstrings activity significantly reduced ATD in all knees. Imran and O’Connor[178] employed a mathematical model to estimate the effects of hamstring activity on ATD and ACL tensile force during simultaneous quadriceps activity. Anterior tibial displacement was estimated and ACL force was modeled at four angles of knee flexion (0°, 30°, 45°, 60°). Calculations showed that hamstrings activity effectively reduced ATD and ACL tensile force at angles of 30° to 60° knee flexion.

The hamstrings and quadriceps are also able to limit knee valgus displacement and the concurrent loads imposed on the MCL as a primary restraint and the ACL as a secondary restraint of excessive joint motion.[35, 246] When the knee assumes a valgus alignment, the medial femoral condyle "lifts off" the medial tibial plateau, a pivot point is created between the lateral femoral condyle and the lateral tibial plateau, and the saggital plane axis of rotation for valgus motion moves lateral to the center of the knee joint.[35, 246] As the saggital plane axis of rotation moves laterally, this creates increased varus (adduction) moment arms for the medial hamstrings and quadriceps to dynamically restrain valgus displacement of the tibia relative to the femur.[35, 159] Lloyd and Buchanan[230] used an *in vivo* experimental configuration to determine the effectiveness of the hamstrings and quadriceps at resisting isolated (flexion, extension) and combined (flexion plus abduction, extension plus abduction) external loads applied to the knee. Loads were applied to the knees of seated subjects using a purpose-built device at six angles of knee flexion (40°, 50°, 60°, 70°, 80°, 90°), and the contribution of the knee muscles to resisting valgus loading was calculated for each flexion angle. Data demonstrated that from 40° to 60° knee flexion the hamstrings and quadriceps were the primary effectors by which external valgus moments were resisted by internal varus moments. Olmstead et al.[285] studied the effects of the hamstrings and quadriceps muscles on valgus stiffness of the knee during the application of an external valgus load. External valgus loads were applied to the knee at 0° knee flexion while submaximal flexion or extension isometric efforts were performed (10% to 20% maximal voluntary isometric contraction (% MVIC)). Valgus knee stiffness was calculated. Results showed that submaximal hamstrings efforts increased valgus stiffness of the knee by 200-280%, thereby making a significant contribution to resisting knee valgus displacement.

Knee internal rotation displacement can also be restrained by the hamstrings and quadriceps.[235, 239] MacWilliams et al.[239] researched the effects of simulated hamstring activity on tibial internal rotation in eight human cadaver knees mounted in a Johns Hopkins Dynamic Knee

Simulator. Internal rotation of the tibia relative to the femur during simulated closed kinetic chain flexion-extension movements was measured using a 3D electromagnetic tracking system. Results showed that simulated medial and lateral hamstring co-contraction significantly reduced tibial internal rotation. Louie and Mote[235] investigated the *in vivo* effects of submaximal hamstrings and quadriceps efforts on torsional stiffness of the knee during the application of internal-external rotation loads. Loads were applied to the knee at 10° and 90° knee flexion with the muscles relaxed and then at sub-maximal efforts (< 25% MVIC). Internal-external rotation stiffness of the knee was calculated for both the relaxed and active conditions. At 10° and 90° knee flexion, the hamstrings alone could increase knee torsional stiffness by 223% and 425%, respectively.

Based on *in vitro*, *in vivo*, and mathematical modeling studies, the hamstrings and quadriceps are capable of resisting undesirable and excessive knee joint movements.[160, 178, 230, 235, 239, 261, 285] The hamstrings and quadriceps are well placed to act as dynamic restraints that generate internal moments to specifically limit ATD, knee valgus, and tibial internal rotation at varying angles of knee flexion and, therefore, are major effectors of knee functional joint stability. Testing and training of the hamstrings and quadriceps is, therefore, important in knee injury prevention, injury rehabilitation, and performance optimization programs due to their biomechanically important role as local dynamic restraints.

2.5.4 Measurement of Knee Functional Joint Stability

There is no universally agreed “gold standard” for defining and/or measuring knee functional joint stability. For the purposes of clinical research and laboratory studies knee functional joint stability has historically been tested using a wide variety of methods such as clinic-based single-leg hop tests[4, 20, 104, 277, 365] and double-leg agility-biased tests (e.g. carioca maneuver),[221, 227] laboratory-based kinematic and kinetic analyses of single- and double-leg functional tasks,[2, 31, 159, 218, 341] and patient self-report questionnaires.[41, 147, 154, 201, 260] According to Lephart et al.[222] objective clinical tests of knee functional joint stability are useful because they indirectly assess an athlete's ability to dynamically control knee joint kinematics during the functional application of shearing and rotational forces. Single-leg hop tests can, subsequently, be considered a representation of the effectiveness of the dynamic restraints to maintain knee functional joint stability.

Sophisticated laboratory-based kinematic and kinetic equipment is not readily available to the clinician and so single-leg hop tests are popular for defining knee functional joint stability in a clinical context.[19, 70, 115, 232, 233] Single-leg hop tests are reliable[48, 73, 156, 207, 269] and valid[70, 73, 305] measures of knee functional joint stability in uninjured and injured physically active adults, are significantly associated with ACL-D and ACL-R patient self-report of functional disability and quality-of-life,[147, 231, 305, 306] and can identify those who will successfully regain knee functional joint stability after injury.[4, 103, 104, 147, 154, 170] It is recommended, therefore, that single-leg hop tests are routinely employed to fully characterize knee functional joint stability and aid in in all aspects of post-injury decision-making.[104, 232, 233]

Depending on the type of single-leg hop test that is chosen by the clinician or researcher, knee functional joint stability is quantified using absolute distance or time variables.[147, 231, 277] Thus, the variable (raw data) extracted from a single-leg hop test represents the distance achieved after the performance of the test or the time taken to perform the test, respectively. For both distance- and time-dependent single-leg hop tests, the clinical premise is that the greater the distance achieved during a test or the lesser the time taken to perform the test, respectively, the more functionally (dynamically) stable the knee. Researchers have normalized distance scores to anthropometric measures (e.g. standing height, leg length) to permit between-subject comparisons.[188, 207, 295] Raw or normalized scores from one limb are then typically compared to the opposite limb and a “limb symmetry index” (LSI) calculated.[20, 70, 277] For injured subjects, the LSI (%) = injured limb score ÷ uninjured limb score × 100.[20, 70, 277]

The single-leg hop test is an important clinical tool that can provide one test of knee functional joint stability in uninjured and injured athletes. The single-leg hop test is, however, an “indirect” measure of knee functional joint stability. This is due to the fact the typical variable of interest generated by a test does not yield specific information about actual knee joint alignment. Laboratory-based 3D analyses of knee kinematics during single-leg hop tests can provide a more “direct” measure of knee functional joint stability due to the ability to estimate actual isolated knee joint alignment in degrees. Several researchers have measured peak knee valgus angle[31, 68, 290] and total knee valgus displacement[118] during 3D analyses of the stance phase of single-leg functional tasks. Both peak knee valgus angle and total knee valgus displacement give more direct and specific information about actual knee joint alignment and, therefore, isolated knee functional joint stability. Laboratory-based 3D kinematic analyses that generate variables such as total knee valgus displacement may better describe knee functional joint stability when considering the combined movements characteristic of noncontact knee injury.

2.5.5 Previous Research: Knee Mechanical Joint Stability vs. Knee Functional Joint Stability

Several research groups have employed anterior tibial displacement (ATD) measurements in bivariate correlation studies to report the relationship between knee mechanical joint stability and functional joint stability. Bivariate correlation (Pearson's Product-Moment Correlation (r); Spearman's Rho (ρ)) is the statistical process by which the strength and direction of a relationship between two variables is mathematically estimated.[143, 298] This statistical process does not determine a "cause and effect" relationship, but rather quantifies how change in the quantity of one variable (x) is related to a change in the quantity of another variable (y).[143, 298] With a "strong" correlation, something can be inferred about y if x is known in advance.[143, 298] According to Vincent[381] a weak correlation exists when $r = 0.50$-0.70. Portney and Watkins[298] and Gokeler et al.[138] state moderate correlations exist when $r = 0.50$-0.75 and $r = 0.60$-0.80, respectively. Strong correlations exist when $r = 0.80$-1.00[61] or $r = 0.90$-1.00.[381] The correlation coefficient has been used to infer the clinical influence of one physical characteristic on another,[115, 138] and can be specifically employed to begin contemplating the potential implications of an intervention for one characteristic relative to another characteristic.[150]

Optimal functional joint stability requires intact mechanical joint stability.[185, 280, 308] It is clinically useful, therefore, to scientifically investigate the relationship between mechanical joint stability and functional joint stability in order to begin considering whether interventions to beneficially change mechanical joint stability may relate to positive changes in functional joint stability. The premise of previous research has been that knee mechanical joint stability defined by ATD is a major contributing factor to knee functional joint stability. Eastlack et al.[103] investigated the relationship between ACL deficiency and knee functional joint stability in 45 ACL-D athletes. Anterior cruciate ligament deficiency was measured by ATD using a KT-2000 arthrometer and functional joint stability was tested by straight-line and multi-directional single-leg hop tests. Results demonstrated no correlation between ATD and performance on all the hop tests. Risberg et al.[313] studied the relationship between ACL-graft integrity and knee functional joint stability in 60 ACL-R patients with a bone-patellar tendon-bone autograft at six, 12, and 24 months post-surgery. Anterior knee laxity was measured by ATD with a KT-1000 arthrometer and functional joint stability was measured by the triple-jump test and the stair-hop test. Results revealed no correlation between ATD and the triple-jump test or between ATD and the stair-hop test. Sekiya et al.[336] examined the relationship between ACL-graft integrity and knee functional joint stability in 107 ACL-R patients with a bone-patellar tendon-bone or hamstring autograft. Anterior knee laxity was measured by ATD using a KT-1000 arthrometer and functional joint stability was measured by the single-leg hop for distance. Results showed a no correlation between variables. Sernert et al.[344] investigated the relationship between ACL-graft integrity and knee functional joint stability in 527 ACL-R patients with a bone-patellar tendon-bone autograft. Anterior knee laxity was measured by ATD with a KT-1000 arthrometer and functional joint stability was measured by the single-leg hop for distance. Data demonstrated a no correlation between variables. These correlation studies collectively and consistently illustrate that isolated saggital plane knee mechanical joint stability defined by the magnitude of ATD is not related to knee functional joint stability defined by single-leg hop tests in ACL-D or ACL-R subjects. As such, anterior knee mechanical joint stability alone may not be a major influence on knee functional joint stability and, therefore, may not need to be considered a priority in noncontact knee injury prevention, rehabilitation, or performance optimization programs.

Other research groups have also employed ATD measurements in multivariate regression studies. Multivariate regression (R^2) provides information about the relationship between variables that bivariate correlation cannot provide.[65, 143, 150] In addition to estimating the strength and direction of relationships between variables, multivariate regression is the statistical process by which the magnitude in change of one variable (outcome variable) is also predicted by two or more other variables (predictor variables).[65, 121, 143, 150] Multivariate regression is, therefore, useful for creating predictive models that can be specifically employed for clinical decision making with regard to how predictor variables make significant contributions to explaining the variance in an outcome variable.[143, 150] Because multivariate regression provides information about relationships between variables that bivariate correlation cannot provide, multivariate regression can be considered a more “powerful” form of statistical analysis.

Knee functional joint stability can be considered a cumulative effect of multiple mechanical and sensorimotor characteristics.[19, 70, 115] It is clinically useful, therefore, to determine the proportion that ATD contributes to knee functional joint stability. Determining the relative contribution that ATD makes to knee functional joint stability alongside other sensorimotor characteristics using multivariate regression techniques may aid in clinical decision making and the prioritization of interventions for those athletes with mechanical joint instability. Hurd et al.[170] studied the influence of ACL deficiency, isometric quadriceps strength, and pre-injury physical activity level on knee functional joint stability in 345 ACL-D patients. Anterior tibial displacement with a KT-1000 arthrometer, isometric quadriceps strength, and score on the Knee Outcome Survey-Activities of Daily Living Scale questionnaire provided the predictor variables. Performance of straight-line and multi-directional single-leg hop tests provided the outcome variables. Results showed that ATD did not contribute to hop test performance. Elmlinger et al.[105] investigated the effects of ACL-graft integrity, isometric and isokinetic knee flexor muscle performance, and a cutaneous sensation visual analogue scale (VAS) on knee functional joint stability in 20 ACL-R patients with a hamstring autograft. Anterior tibial displacement with a KT-1000 arthrometer, isometric and isokinetic muscle performance, and VAS (0 = completely different; 10 = exactly the same) provided the predictor variables.

Forward, medial, and lateral single-leg hop tests provided the outcome variables. Data demonstrated that ATD did not contribute to predicting performance on any of the single-leg hop tests. Risberg et al.[313] investigated the influence of ACL-graft integrity, knee passive range-of-motion (ROM), and isokinetic knee flexion and extension total work on knee functional joint stability in 60 ACL-R patients with a bone-patellar tendon-bone autograft at six, 12, and 24 months post-surgery. Anterior tibial displacement with a KT-1000 arthrometer, knee extension ROM deficit, and isokinetic knee flexion and extension total work at $60°\cdot sec^{-1}$ and $240°\cdot sec^{-1}$ provided the predictor variables. The triple-jump test and the stair-hop test provided the outcome variables. Results showed that ATD did not contribute to predicting the triple-jump or stair-hop test. These regression studies collectively and consistently illustrate that ATD does not significantly contribute to the multivariate prediction of knee functional joint stability defined by single-leg hop tests in ACL-D or ACL-R subjects. Therefore, regression analyses appear to be in agreement with bivariate correlation analyses and confirm that anterior knee mechanical joint stability alone does not make a significant contribution to knee functional joint stability and may not need to be considered a priority in noncontact knee injury prevention, rehabilitation, or performance optimization programs.

2.5.6 Current Evidence: Limitations and Incomplete Knowledge-Base

The existing evidence demonstrates a prevalence of correlation and regression studies reporting the association between ATD and knee functional joint stability. Knee functional joint stability has been “indirectly” measured by the distance achieved during a single-leg hopping task or the time taken to achieve a set distance during a single-leg hopping task. There are no published studies reporting the association between ATD and more “direct” measures of knee functional joint stability such as total knee valgus displacement measured during 3D kinematic analyses of single-leg hop tests. Considering that ATD is accepted as an objective measurement of ACL integrity,[79, 155, 303] and that the ACL is a secondary static restraint to excessive knee valgus motion,[148] the association between ATD and direct measurement of *in vivo* knee valgus using 3D kinematics is of clinical interest. Delineating the association between ATD and direct measurement of total knee valgus displacement may deliver new data that adds to the existing evidence and contributes to the design and development of noncontact knee injury prevention and rehabilitation programs.

2.5.7 Potential Clinical Applications: Interventions to Modify Knee Mechanical Joint Stability

If ATD is significantly associated with total knee valgus displacement, it follows that interventions that enhance the functional properties (i.e. stiffness, ultimate strength) of the ACL may be beneficial in preventing or limiting injury to the ACL itself during a noncontact valgus collapse of the knee. Enhancing the functional properties of the ACL as a secondary static restraint to excessive knee valgus displacement may also be beneficial in preventing injury to the lateral tibiofemoral joint (e.g. lateral meniscus, tibial plateau). With regard to the basic science of soft tissue biomechanics, Mueller and Maluf[268] present a detailed commentary on how the controlled application of mechanical loads can increase the stiffness and strength of ligamentous tissue, and Fitzgerald[113] discusses how the deliberate application of controlled loads via open kinetic chain and closed kinetic chain strength training is likely beneficial for enhancing the mechanical properties of ligamentous tissues in uninjured knees as well as graft complexes in ACL-R knees. With regard to research, Noyes et al.[283] studied how altered physical activity levels affected the ultimate strength of femur-ACL-tibia complexes in primates. Four groups of primates were studied (I: control group; II: total-body plaster cast for eight weeks; III: total-body plaster cast for eight weeks, right leg exposed for daily exercise; IV: total-body plaster cast for eight weeks followed by five months of total-body reconditioning). Animals were culled at the end of the study period and the maximum load to failure of femur-ACL-tibia specimens was tested using an Instron materials testing machine. Data showed that the maximum load to failure in Group IV was higher than that of Group II or III, indicating that five months of reconditioning was able to modify the mechanical properties of the femur-ACL-tibia complex. Morrissey et al.[263] studied the effects of progressive quadriceps open kinetic chain strength training on ATD in human ACL-D and ACL-R subjects. Anterior tibial displacement testing was performed using a Knee Signature System arthrometer before and after six weeks of resisted knee extension training in a 0° to 90° ROM. Results demonstrated how the load used during training was significantly and negatively related to changes in ATD. The authors discuss the responses of soft tissues to altered loading in detail, and how open kinetic chain quadriceps strength training may be beneficial to knee mechanical joint stability defined by the magnitude of ATD. Based on the limited number of primate and human research studies it appears that ATD as a representation of ACL integrity is potentially modifiable with deliberate controlled loading as a result of progressive exercise interventions typically administered in a sports medicine context. Furthermore, considering structured exercise in uninjured humans is well recognized as being able to positively affect the mechanical properties of other soft tissues such as tendons,[210, 304, 345] the anticipated beneficial effects of structured exercise programs on the mechanical properties of the ACL is clinically reasonable.

2.5.8 Summary

Relative to noncontact knee injury in agility-biased team sports, optimal knee joint stability is dependent on the static restraints and dynamic restraints as effectors of knee mechanical joint stability and functional joint stability, respectively. The ACL is a secondary static restraint to excessive knee valgus displacement. Anterior tibial displacement as a variable reflecting integrity of the ACL can be objectively quantified using the KT-1000. Knee functional joint stability can be indirectly estimated using single-leg hop tests and directly measured using 3D analysis of dynamic valgus kinematics. Knee mechanical joint stability defined by ATD does not appear to be significantly associated with knee functional joint stability defined by single-leg hop tests. Studies investigating the association between ATD and 3D measurement of dynamic knee valgus are absent in the published literature. Because there is potential to modify ATD with clinical interventions it is of clinical interest to perform research that delineates the association between ATD and laboratory-based 3D measurement of dynamic knee valgus.

2.6 PROPRIOCEPTION

Normal human movement and optimal physical performance is dependent on effective sensoriomotor control.[134, 135, 350] Sensorimotor control refers to CNS control of posture, whole body movement, and local joint stability.[43, 134, 135, 350, 363] Sensorimotor control operates on a "sensory-motor" basis and is specifically composed of sensory, processing (CNS), and motor components.[43, 133, 220] This means that before the human CNS can generate an appropriate motor output, sensory input is required.[135, 319, 350]

The sensory component of sensorimotor control is termed proprioception.[139, 223, 224, 249, 319] Proprioception is historically and classically defined as the sense of position and movement of the joints and limbs, which correspond to joint position sense (JPS) and kinesthesia, respectively.[249, 308, 319] More recently, proprioception has also been defined as including the sense of tension/resistance to movement, which is designated force sense.[308, 310, 362] Some authors have additionally proposed that the timeframe between the onset of a knee perturbation and the onset of reflex muscle activity (i.e. post-perturbation reflex latency) should be considered a further component of proprioception,[27] although this has not been widely accepted. Proprioception is, therefore, typically defined as being composed of JPS, kinesthesia, and force sense.[249, 308, 310, 319]

2.6.1 Proprioception and Role in Knee Functional Joint Stability

Lephart et al.[223] and Riemann and Lephart[308] discuss how proprioception is the result of afferent information generated by mechanoreceptors (proprioceptors) in the peripheral areas of the body for the purpose of maintaining local joint stability and overall postural control. A mechanoreceptor is a highly specialized sensory nerve ending which is specifically stimulated by mechanical deformation.[21, 22, 249] Mechanoreceptors are transducers that convert mechanical stimuli into electrical signals for transmission to the CNS.[21, 22, 139, 249] Mechanoreceptors are located in both the non-contractile tissues of synovial joints and muscle-tendon units surrounding a joint. Mechanoreceptors in the non-contractile tissues of joints include Pacinian corpuscles, Ruffini corpuscles, and Mazzoni corpuscles.[22, 161, 249] Mechanoreceptors in the tissues of the muscle-tendon unit include the muscle spindle and Golgi Tendon Organ (GTO), respectively.[139, 249, 319] Of the joint and muscle-tendon mechanoreceptors, the muscle spindle is the most sensitive and potent of all proprioceptors.[129, 139, 319]

Stimulation of a mechanoreceptor by mechanical stimuli results in the generation of an action potential at the mechanoreceptor nerve ending itself, which is then propagated and transmitted proximally to the CNS by an afferent neuron.[21, 22, 249] Sensory (proprioceptive) information is integrated at all three levels of sensorimotor control in the CNS: the spinal cord, brainstem, and cerebral cortex.[43, 133, 220] At the spinal cord level, proprioceptor neurons make monosynaptic and polysynaptic connections with the cell bodies of alpha (α) and gamma (γ) motor neurons which innervate the extrafusal and intrafusal muscle fibers, respectively.[139, 182, 184, 359] At the brainstem level, proprioceptive information transmitted by the spinocerebellar tract is relayed via the medulla to motor control nuclei in the spinocerebellar cortex.[132, 135, 248] At the cerebral cortex level, proprioceptive information is transmitted to the primary somatosensory cortex by the dorsal column-medial lemniscal system.[133, 135, 248] The spinocerebellar cortex nuclei and primary somatosensory cortex nuclei then transmit proprioceptive information to the primary motor cortex via the fastigial nuclei and transcortical axons, respectively.[132, 135] At spinal cord level, proprioceptive information is used for feedback motor control of skeletal muscle, whereas at brainstem and cerebral cortex level proprioceptive information is primarily used for feedforward motor control of skeletal muscle.[133, 134, 139]

Proprioceptive information inputs to all levels of the CNS that are involved in stimulating extrafusal and intrafusal muscle fiber activity as the product of feedback and feedforward sensorimotor control.[133, 135, 319] With regard to the anatomical tissues involved in a noncontact valgus collapse of the knee, mechanoreceptors have been identified in the ACL, MCL, and meniscus.[83, 196, 335] Mechanical stimulation of the ACL and MCL evokes reflex activation of extrafusal and intrafusal muscle fibers around the knee.[54, 92, 127, 184, 185, 359] Stimulation of extrafusal and intrafusal muscle fibers increases muscle stiffness which, in turn, enhances instantaneous stability of the joint underlying the muscles, as well as increases the sensitivity and reflex responses of the joint's muscles to subsequent joint perturbations.[43, 182, 185, 225, 319] Proprioceptive (sensory) information, therefore, directly mediates skeletal muscle (motor) responses throughout the CNS for the purposes of maintaining joint stability,[43, 220, 363] and measurement of knee proprioception is necessary to gain understanding of the sensory contribution to sensorimotor control of knee functional joint stability in uninjured and injured athletes.

2.6.2 Measurement of Knee Proprioception

Proprioception is composed of the modalities of JPS, kinesthesia, and force sense.[308, 310] Because proprioception has, however, been historically and classically defined as being composed of only JPS and kinesthesia,[249] scientific measurement of knee proprioception has been dominated by tests of knee JPS and kinesthesia. Tests are most frequently performed using an open kinetic chain configuration in order to determine knee proprioception in isolation from other joints in the lower limb (e.g. hip, ankle). The different proprioceptive modalities require different measurement techniques and subsequent variable designation.[310] Knee JPS has been estimated under both passive and active conditions, which correspond to where muscle is inactive and active, respectively. Knee kinesthesia has been estimated under predominantly passive conditions. Passive test conditions are thought to bias joint proprioceptors because muscle tissue is relatively relaxed and inactive whereas active test conditions stimulate both joint and muscle-tendon proprioceptors.[310, 325, 352]

Knee JPS tests determine the subject's ability to reproduce a previously determined and experienced knee joint target angle measured in degrees (°).[16, 32, 57, 58, 99, 361] Researchers have used a variety of instrumentation and configurations to measure saggital plane-biased (flexion-extension) knee passive reproduction of passive positioning (PRPP),[57, 58, 292] active reproduction of passive positioning (ARPP),[16, 32, 57, 58, 126] and active reproduction of active positioning (active joint position sense (AJPS)).[57, 58, 99, 171, 173] Other researchers have used transverse plane-biased (internal-external rotation) instrumentation and configurations to measure knee AJPS.[265-267] The variables typically extracted from these different knee JPS tests include absolute error (AE; °) and relative error (RE; °).[16, 58] Absolute error is the difference between the target (reference) angle and the reproduced angle without consideration for whether the subject positions the knee before (undershoot; negative value) or after (overshoot: positive value) the target angle, whereas relative error represents the difference between the target angle and the reproduced angle with consideration for undershoot or overshoot and being expressed as a signed value.[16, 58] Whether AE or RE is used to express knee JPS, the common clinical interpretation is that the smaller the difference between the target angle and the reproduced angle the more sensitive the subject's proprioceptive acuity.

Knee kinesthesia is commonly measured using threshold to detection of passive motion (TTDPM).[310] The TTDPM test determines the subject's ability to sense the onset of passive knee joint motion measured in degrees (°). Researchers have used a variety of instrumentation, configurations, and speeds (e.g. $0.25°\cdot sec^{-1}$, $0.50°\cdot sec^{-1}$) to study saggital plane-biased (flexion-extension) knee passive kinesthesia using TTDPM.[23, 41, 42, 57, 58, 126, 325] Other researchers have used transverse plane-biased (internal-external rotation) instrumentation and configurations to measure knee TTDPM.[272, 274] The commonly extracted variable from a TTDPM test is the amount of joint motion that occurs before the subject becomes aware that joint motion has actually commenced.[23, 41, 42, 126, 325] Similar to knee JPS tests, the common clinical interpretation is that the smaller the amount of joint motion between the onset of the test and the subject's detection of joint motion the more sensitive the subject's proprioceptive acuity.

To understand the proprioceptive contribution to sensorimotor control of knee functional joint stability, knee proprioception tests should be performed. The literature demonstrates a wide variety of saggital (flexion-extension) and transverse plane (internal rotation-external rotation) knee proprioception tests. To date, there are no published studies using frontal plane (varus-valgus) tests of JPS or kinesthesia in uninjured or injured athletes. The findings of previous research using tests of knee proprioception can potentially help inform the relative contribution and importance of the different modalities of proprioception to knee functional joint stability.

2.6.3 Previous Research: Knee Proprioception vs. Knee Functional Joint Stability

Research groups have investigated the association between knee proprioception and knee functional joint stability using bivariate correlations in uninjured subjects. The basis of such studies lies in an attempt to determine the clinical relevance of knee proprioception to knee functional joint stability.[138] Optimal functional joint stability is considered a cumulative effect of multiple characteristics, including proprioception.[185, 280, 308] It is clinically useful, therefore, to scientifically investigate the relationship between proprioception and functional joint stability in order to begin considering whether interventions to positively change proprioception may relate to beneficial changes in functional joint stability. Drouin et al.[99] researched the relationship between knee proprioception and functional joint stability in 40 uninjured subjects. Knee proprioception was tested with a seated AJPS test that biased eccentric quadriceps activity by requiring movement from 0° to 30° knee flexion, and functional joint stability was measured using the single-leg crossover hop for distance test. Data showed there was no correlation between variables. Madden[240] researched the relationship between knee proprioception and functional joint stability in 23 uninjured subjects. Knee proprioception was tested with a seated AJPS test that biased eccentric quadriceps activity by requiring movement from 0° to 30° knee flexion, and functional joint stability was measured using the single-leg hop for distance test. Data demonstrated an absence of correlation between variables.

Research groups have also investigated the association between knee proprioception and knee functional joint stability using bivariate correlations in injured subjects. Borsa et al.[42] studied the relationship between knee proprioception and functional joint stability in 29 ACL-D athletes. Knee proprioception was measured by a seated TTDPM apparatus that moved the knee into both flexion and extension, and functional joint stability was defined by the single-leg hop for distance test. Results demonstrated weak correlations (r = -0.46 - -0.56, $P < 0.05$) between variables. Friden et al.[125] investigated the relationship between knee proprioception and functional joint stability in 17 ACL-D patients. Knee proprioception was assessed with a side-lying TTDPM instrumentation that moved the knee into flexion and extension, and functional joint stability was determined by the single-leg hop for distance test. Data showed weak correlations (r = -0.32 - -0.58, P not reported) between variables. Katayama et al.[194] studied the relationship between knee proprioception and functional joint stability in 32 ACL-D patients. Knee proprioception was measured using a seated ARPP JPS test that biased concentric quadriceps activity by requiring movement from 90° to 0° knee flexion, and functional joint stability was measured using the single-leg hop for distance test and the single-leg vertical hop tests. Results showed weak correlations (r = -0.38 - -0.50, $P < 0.05$) between variables. Risberg et al.[312] studied the relationship between knee proprioception and functional joint stability in 20 ACL-R subjects with a bone-patellar tendon-bone autograft. Knee proprioception was assessed by a seated TTDPM device that moved the knee into both flexion and extension, and functional joint stability was measured by the single-leg hop for distance test and the stair-hop test. Data showed weak correlations ($r = 0.15 - 0.40$, P not reported) between variables. These correlation studies collectively and consistently illustrate that knee proprioception defined by passive and active JPS tests and TTDPM tests is not strongly related to knee functional joint stability defined by straight-plane and multi-directional single-leg hop tests in uninjured and injured subjects.

In addition to bivariate correlation models, it is also clinically useful to determine the proportion that knee proprioception contributes to knee functional joint stability using multivariate regression techniques. Identifying the proportion that knee proprioception contributes to knee functional joint stability potentially aids clinical decision making and the prioritization of interventions. There is a lack, however, of published multiple regression studies investigating the prediction of knee functional joint stability defined by single-leg hop tests. Borsa et al.[41] investigated the influence of knee proprioception, single-leg static balance, single-leg hop for distance, and isometric quadriceps strength on knee functional joint stability in 29 ACL-D subjects. Predictor variables included the Lysholm Knee Scale and the Cincinnati Knee Scale questionnaire scores, a TTDPM limb symmetry index (LSI), a single-leg static balance LSI, a single-leg hop for distance LSI, and an isometric quadriceps LSI. The outcome variable was a subjective rating of knee function visual analogue scale (0 = complete loss of function, 100 = level of knee function prior to injury). Results showed that knee proprioception defined by the TTDPM LSI did not significantly contribute to subjects' subjective rating of knee functional joint stability. Nagai et al.[273] researched the contributions of knee proprioception and isometric hamstrings and quadriceps strength on knee functional joint stability in 50 uninjured subjects using two multiple regression models. Predictor variables for both models included knee flexion and extension TTDPM at 0.25°·sec^{-1} and hamstring and quadriceps isometric peak torque at an angle of 45° knee flexion. For one model, the outcome variable was initial contact knee flexion angle during the single-leg stop-jump. For the other model, the outcome variable was total knee flexion excursion during the single-leg stop-jump. For the initial contact regression model, analysis demonstrated a significant regression model ($R^2 = 0.27$, $P = 0.001$) where knee flexion TTDPM was a significant variable (Coefficient value = 2.1, $P < 0.05$). For the total knee flexion excursion model, TTDPM did not make a contribution. Roberts et al.[315] studied the effects of knee laxity, proprioception, and isokinetic muscle performance on knee functional joint stability in 36 ACL-D patients. Predictor variables included ATD side-to-side difference, a summed flexion and extension TTDPM index, and a summed concentric isokinetic hamstrings and quadriceps peak torque index at 60°·sec^{-1}. The outcome variable was the single-leg hop for distance. Statistical analysis demonstrated a significant regression model was generated ($R^2 = 0.52$, $P < 0.01$) of which the TTDPM index was a significant variable (Coefficient value = -11.8, $P < 0.01$). Based on the bivariate correlation and regression analyses cited here, knee proprioception defined by a variety of JPS and kinesthesia tests does not seem to make a consistently strong contribution to knee functional joint stability. The clinical relevance, therefore, of knee proprioception measured using quadriceps AJPS tests and knee flexion and extension TTDPM tests relative to knee functional joint stability is unclear.

2.6.4 Current Evidence: Limitations and Incomplete Knowledge-Base

The existing evidence-base demonstrates a wide range of correlation and regression studies investigating the association between knee proprioception and knee functional joint stability. Knee proprioception has been operationally defined by a variety of modalities including JPS and kinesthesia. Of published correlation and regression studies, many fail to report the reliability of the tests used to generate the variables included in statistical analyses,[99, 194, 240, 315] and so the validity of raw data is questionable. Further, authors employing correlation and regression research designs consistently fail to report any *a priori* power analyses,[99, 125, 194, 240, 312, 315] and so it is possible that many studies are underpowered with regard to the number of subjects tested.

The majority of the JPS and kinesthesia tests published in the literature are not "functional" since they are passive in nature where muscle tissue is relaxed and relatively inactive. This may explain, for example, the consistently weak associations found between TTDPM tests and knee functional joint stability. Recent expert opinion has, therefore, considered that passive measures of knee proprioception such as TTDPM are inadequate for characterizing knee sensory function and are lacking in clinical and functional relevance.[138]

Active tests of proprioception such as ARPP and AJPS typically involve moving from a defined starting position (e.g. 90° knee flexion) to a predetermined target angle (e.g. 45° knee flexion), and are typically performed using concentric quadriceps muscle actions.[57, 58, 171, 173, 194] These active tests clearly do not employ eccentric knee muscle actions which generate the most powerful stimulus for the muscle spindle,[139, 319] and that are critical for decelerating joint perturbations and absorbing joint impact forces.[9, 213, 229] Few authors have studied quadriceps AJPS using eccentric muscle actions moving from a defined starting position (e.g. 0° knee flexion) to a predetermined target angle (e.g. 30° knee flexion).[99, 240] There does not appear to be any published work that investigates AJPS tests using eccentric hamstring muscle activity, which may be particularly important when considering the role of the hamstring muscles as dynamic restraints to excessive knee valgus, ATD, and tibial internal rotation[239, 261, 285] as components of a noncontact valgus collapse of the knee.

Gokeler et al.[138] state that new tests of knee proprioception are needed. Knee proprioception tests that incorporate eccentric hamstring muscle activity may deliver new data that elucidates a strong association between knee proprioception and knee functional joint stability. This data may then inform noncontact knee injury prevention and rehabilitation programs in a clinically relevant and useful way.

2.6.5 Potential Clinical Applications: Interventions to Modify Knee Proprioception

If active tests of knee proprioception are significantly associated with knee functional joint stability defined indirectly by single-leg hop tests or directly by 3D analysis of dynamic knee valgus, it follows that interventions designed to improve active proprioceptive acuity may be useful in noncontact knee injury prevention and rehabilitation programs. The muscle spindle is the most sensitive and potent of all proprioceptors and is always stimulated with active movements as a consequence of alpha-gamma coactivation.[139, 319] Human kinesthetic acuity is significantly enhanced under active conditions where muscle is stimulated.[129, 367] Any active exercise, therefore, could be considered “proprioceptive training” since it will generate a barrage of proprioceptive discharges from muscle-tendon mechanoreceptors.[74, 214] Docherty et al.[97] administered a six week (× 3 training sessions/week) exercise program to 20 subjects with functional ankle instability. Ankle inversion, eversion, plantarflexion, and dorsiflexion AJPS was measured before and after the intervention using a custom-built device. Exercises consisted of open kinetic chain ankle inversion, eversion, plantarflexion, and dorsiflexion elastic resistance strength training. Following the intervention, ankle inversion and plantarflexion AJPS was significantly improved. Waddington et al.[384] studied the effects of wobble-board and jump-landing training on knee active kinesthetic discrimination in 88 uninjured male Australian Rules

Football players. Kinesthetic discrimination was measured with a custom-built device that allowed subjects to self-pace weight-bearing knee flexion movements in a forward lunge position before and after the intervention. Eight weeks (× 3 training sessions/week) of single- and double-leg balance and jump-landing training was performed. Results showed a significant improvement in knee kinesthetic discrimination after the intervention. Based on these works, active measures of proprioception as a representation of peripheral joint proprioceptive acuity are potentially modifiable with selected exercise interventions such as elastic resistance strength training, single-leg wobble-board training, and single-leg jump-landing drills that are common to sports medicine environments.

2.6.6 Summary

Proprioception is the sensory component of sensorimotor control. Proprioception is composed of JPS, kinesthesia, and force sense, and is the result of afferent information generated by multiple mechanoreceptors in non-contractile joint tissues as well as the muscle-tendon unit. Of all proprioceptors, the muscle spindle is the most sensitive and potent. Proprioceptive information is transmitted to, and modifies motor output at, all levels of the CNS. Proprioceptive information, therefore, directly mediates skeletal muscle stiffness and functional joint stability. Knee proprioception has most commonly been measured using passive and active (concentric-biased) JPS and passive kinesthesia. These methods of measuring knee proprioception are not strongly associated with knee functional joint stability defined by single-leg hop tests. Studies investigating the association between knee AJPS tests that incorporate eccentric hamstring muscle activity and knee functional joint stability defined by single-leg hop tests or 3D analysis of dynamic knee valgus are absent from the literature. There is potential for active proprioception to be modified with selected exercise interventions and, therefore, the association between hamstring eccentric-biased AJPS tests and knee functional joint stability merits investigation.

2.7 NEUROMUSCULAR CONTROL

Neuromuscular control is the motor component of sensorimotor control and is defined as activation of the dynamic restraints in preparation for and in response to joint motion and loading for the purpose of maintaining and restoring functional joint stability.[308, 309] In essence, neuromuscular control is the efferent (motor) response to an afferent (sensory) signal concerning joint stability.[43, 225, 226] Effective neuromuscular control must, therefore, be preceded by appropriate and sufficient proprioceptive information transmitted to the CNS. Neuromuscular control is proprioceptively-mediated activation of the dynamic restraints in order to stress shield non-contractile tissues from potentially injurious forces and facilitate ideal arthrokinematics during the execution of specific movement patterns.[75, 225, 308] Neuromuscular control manifests as the active restraint of excessive joint motion, the coordinated dampening of joint loads, and the facilitation of efficient movement patterns, and is composed of feedforward and feedback neuromuscular control.[74, 223, 309]

Feedforward neuromuscular control involves preparatory activation of and force generation by the dynamic restraints before the onset of afferent stimuli signaling joint loading and/or perturbation.[133, 223, 363] Substantial previous experience of a specific movement pattern and the sensory (proprioceptive) stimuli it generates must have occurred in order for the CNS to create a feedforward motor strategy that preprograms skeletal muscle before joint loading and/or perturbation,.[133, 134, 223] Proprioceptive feedback from previous experience (e.g. training) is used to modify feedforward motor programs stored in supraspinal centers in the cerebellar and cerebral cortices.[133, 135, 334] Feedforward preactivation of the skeletal muscles increases muscle stiffness resulting in greater sensitivity for and reaction to unanticipated single-joint loading and/or perturbation as well as whole body postural disequilibrium.[133, 225, 363] Feedforward preactivation of skeletal muscles is, therefore, clinically important in order to prevent potentially injurious forces being imposed on the musculoskeletal system when the foot naturally collides with the ground during the gait cycle and other highly dynamic athletic tasks such as jump-landings.[330-332]

Feedback neuromuscular control involves an almost instantaneous ‘at-that-moment-in-time’ motor response to proprioceptive information.[74, 225, 308] With specific regard to functional joint stability, feedback neuromuscular control is reactive activation of and force generation by the dynamic restraints after the onset of sensory stimuli signaling joint loading and/or perturbation.[74, 225, 308] At the instant of a noncontact valgus collapse of the knee, feedback neuromuscular control is critical for limiting excessive knee valgus displacement and preventing injury to the ACL, MCL, and lateral meniscus.

Understanding feedforward and feedback neuromuscular control of dynamic restraints local to the knee will aid in the identification of characteristics that are potentially modifiable with targeted clinical interventions. Such interventions may then be validated as critical elements for enhancing feedforward and feedback neuromuscular control and, in turn, become important components of noncontact knee injury prevention and rehabilitation programs.

2.7.1 Feedforward Neuromuscular Control and Role in Knee Functional Joint Stability

Feedforward neuromuscular control is defined as preparatory activation of and force generation by the dynamic restraints before joint motion, loading, and/or perturbation.[225, 308, 363] Feedforward neuromuscular control manifests as a specific increase in muscle activity prior to the moment of actual joint loading following the onset of ground-contact impact forces during the gait cycle and jump-landings.[100, 102, 331, 332, 365, 369] Muscle activity as a result of feedforward neuromuscular control has been designated by Lephart et al.[217] as "preactivity". Increased muscle activity results in a proportional increase in muscle stiffness.[119, 120, 186, 257, 353] In a biomechanical context, muscle stiffness is defined as the ratio of change in muscle force to change in muscle length.[76, 183, 187] A specific increase in muscle stiffness results in an increase in resistance to lengthening of that muscle-tendon unit.[76, 257, 353] Increased feedforward muscle activation and stiffness, therefore, result in increased stiffness (stability) of the joint underlying the muscles and a greater resistance to joint displacement.[175, 183, 225, 235, 257, 353] Preactivated muscles consequently protect the underlying joint from excessive displacement, loading, and/or perturbation, and shield the joint's intracapsular and extracapsular inert tissues from potentially injurious forces.[175, 182, 183, 225, 309] The role of feedforward neuromuscular control and preparatory muscle stiffness is likely magnified in its importance in specific instances where mechanical joint stability has been previously compromised (e.g. ACL-deficiency, MCL-deficiency) due to previous traumatic injury.[225, 252, 309, 363]

Modulation of muscle stiffness is also thought to affect the way loads are transmitted to the muscle spindle.[225, 309] When muscle activation is increased and, in turn, muscle stiffness is increased, stretching loads are more readily transmitted to the muscle spindle as evidenced by enhanced active muscle stretch reflexes.[108, 212, 301] Thus, feedforward activation of skeletal muscle can also augment the feedback neuromuscular control response to unanticipated joint loads in order to further mitigate excessive joint displacement.[225, 309]

2.7.2 Measurement of Feedforward Neuromuscular Control

Feedforward neuromuscular control is composed of an activation component and a force generation component. According to Riemann and Lephart[310] and Shultz and Perrin,[349] the preparatory muscle activation component (preactivity) can be measured by electromyography (EMG). Of particular usefulness in a sports medicine environment for investigating how the CNS activates skeletal muscle during athletic tasks is surface EMG (sEMG).[310, 349] According to Dhyre-Poulsen et al.,[102] the force generation component of feedforward neuromuscular control cannot be easily measured during functional athletic tasks such as landing from a jump. Much knee sensorimotor control research has, therefore, modeled feedforward neuromuscular control using sEMG to report a variety of muscle activation characteristics.[53, 90, 91, 290, 365] Different variables and units of measurement can be created to describe the desired aspects of muscle activation characteristics, with common variables being the onset, offset, mean activation, and peak activation, along with agonist-antagonist or synergist coactivation ratios.[310, 349] Mean activation and peak activation are considered useful for quantifying muscle activation: mean activation is obtained by averaging the rectified EMG values recorded over a defined timeframe; peak activation is obtained by identifying the single largest EMG value recorded over a defined timeframe.[24, 358, 374, 391] Although useful, mean activation and peak activation provide a limited means of quantifying muscle activation since finer details about the magnitude of muscle activation or duration of muscle activation, respectively, are lost.[358] A more thorough means of quantifying muscle activation over a defined timeframe is that of integrated EMG (iEMG).

Integrated EMG is the process of calculating the area under the rectified EMG curve and expresses cumulative muscle activation accounting for both magnitude and duration of activation.[24, 137, 358, 374, 391] As such, iEMG is recommended by some as the preferred means of quantifying sEMG data.[374] The choice of sEMG variable and its unit of measurement is, ultimately, determined by the muscle activation characteristics that are of most relevance to the researcher's study design and research question.

2.7.3 Feedback Neuromuscular Control and Role in Knee Functional Joint Stability

Feedback neuromuscular control involves reactive activation of and force generation by the dynamic restraints.[74, 225, 308] Muscle activity as a result of feedback neuromuscular control has been designated by Lephart et al.[217] as "reactivity". Riemann and Lephart[308] state that feedback neuromuscular control of functional joint stability involves unconscious activation of skeletal muscles as dynamic restraints to excessive joint motion. Use of the term "unconscious" infers activation of the dynamic restraints is involuntary and outside of conscious control. Involuntary muscle activity is classified as reflex behavior where a "reflex" is a stereotyped involuntary muscle response to a specific sensory stimulus.[139] Several authors have reported reflex activation of the hamstring muscles in response to mechanical stimuli designed to load the human ACL,[26, 127, 174] and reflex activation of the medial hamstrings and medial quadriceps in response to mechanical stimuli designed to load the MCL.[54, 92] Other authors have documented reflex activation of the hamstring muscles in response to electrical stimulation of the human ACL,[101, 296, 373] and reflex activation of the medial hamstrings and medial quadriceps in response to electrical stimulation of the MCL.[197] These studies collectively suggest that specific ligament-muscle sensory-motor circuitry is hardwired into the human CNS. This sensory-motor circuitry mediates feedback neuromuscular control of functional joint stability: feedback neuromuscular control is specifically directed at muscles that act as antagonists to the direction of joint motion and ligament loading perceived by the CNS. Considering potential ACL and MCL loading during a noncontact valgus collapse of the knee, reflex activation of and force generation by the hamstrings and medial quadriceps is a highly desirable motor program.

Once a muscle has been reflexively activated by the CNS, timely generation of force is of great importance to neutralize excessive joint perturbations in potential injury situations.[175, 395] The electromechanical delay (EMD) and rate of force development (RFD) are important components of reactive force generation.[74, 175, 225] The EMD is the timeframe between the onset of reactive muscle activity and the onset of measurable force, and represents the sequence of physiological events between the first detection of muscle depolarization via EMG and the first detection of a force.[29, 190, 392] The RFD is the timeframe between the onset of measurable force and the achievement of a defined quantity of force, and represents the sequence of physiological events involved in rapid sarcomere shortening and continually rising force development.[1, 29, 149, 190] The timely generation of hamstrings and quadriceps muscle forces and the resulting joint torques is needed if excessive joint displacements are to be rapidly neutralized during a noncontact valgus collapse of the knee. The determination of hamstrings and quadriceps force generating characteristics is, therefore, critical when evaluating the feedback neuromuscular control mechanism and considering the potential content of noncontact knee injury prevention and rehabilitation programs.

2.7.4 Measurement of Feedback Neuromuscular Control

Feedback neuromuscular control is composed of an activation component and a force generation component. As for feedforward neuromuscular control, the reactive muscle activation component (reactivity) can be measured and characterized using sEMG and similar variables can also be created.[310, 349] According to Riemann and Lephart[310] the determination of muscle performance characteristics is an important method for the assessment of neuromuscular control. Specifically, muscle performance characteristics study the force generating component of feedback neuromuscular control. Measurement of the EMD and RFD have historically been employed by physiologists as variables to define and measure specific muscle performance characteristics considered important for the rapid development of muscle force/joint torques.[1, 29, 392] A major limitation of these variables with regard to clinical application, however, is that they are extracted from isometric (static) tests performed within highly complex apparatus at a fixed "non-functional" ROM (e.g. 70° or 90° knee flexion).[1, 190]

An alternative means of dynamic muscle performance assessment that is considered valuable in the sports medicine context is that of isokinetic testing.[60, 191, 310, 333] Isokinetic testing can be performed using concentric or eccentric muscle actions, at different velocities (e.g. $60°\cdot sec^{-1}$, $120°\cdot sec^{-1}$, $240°\cdot sec^{-1}$), and can generate a range of different variables such as peak torque, peak torque to bodyweight, average peak torque, angle of peak torque, total and peak work, average and peak power, and torque acceleration energy.[60, 191] The value of isokinetic testing lies in its ability to generate a range of variables that give useful information about different muscle performance characteristics that cannot be extracted from other muscle performance tests commonly employed in a clinical context (e.g. manual muscle test, handheld dynamometry, one repetition maximum).

Concentric isokinetic time-to-peak torque (TTPT) in milliseconds is a variable that represents the ability to rapidly and dynamically generate torque.[60] Concentric isokinetic TTPT has frequently been employed as a measure of knee feedback neuromuscular control in the sports medicine literature,[320, 375, 395] and expert consensus considers the reduction of TTPT to be an important goal in noncontact knee injury prevention programs.[146] Shorter TTPT timeframes represent faster reactive force generation and the potential for more rapid neutralization of post-perturbation joint displacements. Shorter TTPT timeframes are, therefore, highly desirable for enhancing and optimizing feedback neuromuscular control of knee functional joint stability.[176, 395, 397] Although TTPT is considered an important goal in noncontact knee injury prevention programs,[146] concentric isokinetic peak torque has historically most commonly been employed to operationally define muscle performance relative to knee functional joint stability. The findings of existing research can help inform the relative contribution of isokinetic muscle performance to knee functional joint stability.

2.7.5 Previous Research: Knee Muscle Activation Characteristics vs. Knee Functional Joint Stability

Optimal functional joint stability is considered a cumulative effect of multiple characteristics, including feedforward and feedback neuromuscular control.[43, 115, 182, 219, 363] Because feedforward and feedback neuromuscular control both include muscle activation as a principal component, some research groups have studied the association between various muscle activation characteristics and knee functional joint stability using bivariate correlation and multivariate regression study designs. It is clinically useful to study the association between muscle activation characteristics and knee functional joint stability in order to begin considering whether interventions designed to alter the muscle activation components of neuromuscular control might result in advantageous changes in overall knee functional joint stability. Brown et al.[53] investigated the multivariate association between rectus femoris, vastus lateralis, and lateral hamstring preactivity and knee functional joint stability in 35 uninjured female agility-biased team sports athletes. Muscle preactivity was defined as root mean square sEMG muscle activity expressed as %MVIC for 100msec prior to ground-contact, and knee functional joint stability was defined as peak knee valgus angle during the first half of stance phase of a forward single-leg landing and lateral change-of-direction task. No sEMG variables emerged as significant predictors of peak knee valgus angle. Palmieri-Smith et al.[290] studied the multivariate association between rectus femoris, vastus lateralis, vastus medialis, lateral hamstrings, medial hamstrings, and gluteus medius preactivity and knee functional joint stability in 21 (11 female, 10 male) uninjured recreationally active subjects. Muscle preactivity was defined as the root mean square muscle activity expressed as %MVIC for 100msec prior to ground-contact, and knee functional joint stability was defined as peak knee valgus angle during the landing phase of a single-leg forward hop. Data analyses with both gender groups combined did not reveal any significant predictors of peak knee valgus angle. However, data analyses for the female subjects alone demonstrated that a higher peak knee valgus angle was significantly predicted by increased vastus lateralis and lateral hamstring preactivity. Beard et al.[26] investigated the bivariate relationship between hamstring reactivity ("reflex hamstring contraction latency" (RHCL)) and knee functional joint stability in 30 ACL-D patients. The RHCL was defined as the timeframe between the moment of a partial weight-bearing anterior tibial displacement (accessory motion displacement) induced by a compressed air piston fired into the superior aspect of the posterior calf, and the onset of sEMG-detected hamstrings activation. Knee functional joint stability was defined by a knee-specific patient questionnaire score. Data showed no significant correlation between variables. A significant and moderate correlation ($r = 0.62$, $P < 0.05$) was, however, reported between the RHCL "differential" and an "instability score", but neither of these variables were clearly defined by the authors. Beard et al.[25] determined the bivariate relationship between hamstring reactivity and knee functional joint stability as part of a supplementary analyses for a randomized controlled trial of two rehabilitation programs for ACL-D patients. Twenty patients were randomized to a "traditional regime" (strength training-biased exercises) and 23 to a "proprioceptive regime" (single-leg balance/wobble board/roller board/ballistic exercises). Hamstring reactivity was defined by the pre- to post- change in RHCL and knee functional joint stability was defined by the pre- to post- change in a knee-specific patient questionnaire score. The supplementary analyses pooled all subjects into one group. A significant and weak correlation was found between variables ($r = 0.30$, $P < 0.05$).

Few research groups have published work that reports bivariate or multivariate associations between hamstrings or quadriceps preactivity or reactivity and knee functional joint stability defined by single-leg hop tests, knee valgus kinematics, or patient questionnaires. Based on the work reviewed above, it remains unclear as to how knee muscle preactivity or reactivity is statistically and objectively associated with knee functional joint stability. With specific regard to noncontact knee injuries, the extent of association between hamstrings preactivity and reactivity and direct measurement of knee valgus has yet to be elucidated.

2.7.6 Current Evidence for Knee Muscle Activation Characteristics: Limitations and Incomplete Knowledge-Base

Existing research demonstrates some correlation and regression studies that investigate the associations between feedforward and feedback muscle activation and knee functional joint stability defined by single-leg hop tests, knee valgus kinematics, and patient questionnaires. These studies use a variety of EMG-based variables to characterize muscle preactivity and reactivity. Of published correlation and regression studies that include preactivity and/or reactivity variables relative to single-leg hop tests, knee valgus kinematics, or patient questionnaires, most do not report the reliability of the procedures used to generate the EMG-based variables included in the statistical analyses,[25, 26, 53, 290] and so the validity of raw data is unknown. Further, most authors employing correlation and regression research designs do not report an *a priori* power analysis,[25, 26, 290] and so these studies may be underpowered. Because basic information regarding study design/methods is missing from most existing published reports the interpretation and clinical application of data from such reports is limited. Despite the perceived importance of feedforward neuromuscular control and preparatory muscle stiffness in knee functional joint stability,[175, 183, 225, 308] it appears that few research groups have published correlation or regression studies that employ EMG-based variables for describing feedforward or feedback muscle activation characteristics relative to single-leg hop tests, knee valgus kinematics, or patient questionnaires. As such, the current evidence-base is incomplete with regard to data describing local knee muscle activation characteristics as components of feedforward and feedback neuromuscular control. Further EMG-based research is needed to add new data to the literature and potentially lend greater assistance to those wishing to consider the modification of muscle preactivity and reactivity in knee injury prevention and rehabilitation programs.

2.7.7 Previous Research: Knee Muscle Force Generating Characteristics vs. Knee Functional Joint Stability

Optimal functional joint stability is considered a cumulative effect of multiple characteristics, including performance of the dynamic restraints (muscles).[185, 280, 308, 310] It is clinically useful, therefore, to scientifically investigate the relationship between muscle performance characteristics and functional joint stability in order to begin considering whether interventions to positively change muscle performance characteristics may relate to beneficial changes in functional joint stability. The relationship between concentric isokinetic muscle performance and knee functional joint stability has been studied using bivariate correlation paradigms by some research groups in uninjured subjects. Greenberger and Paterno[142] determined the relationship between knee concentric isokinetic muscle performance and functional joint stability in the dominant and non-dominant limbs of 20 uninjured subjects. Isokinetic muscle performance was specified by quadriceps peak torque at $240°\cdot sec^{-1}$ and knee functional joint stability was defined by the single-leg hop for distance. Findings showed correlations between variables for the dominant ($r = 0.78$, $P < 0.05$) and non-dominant ($r = 0.64$, $P < 0.05$) limbs. Pincivero et al.[295] studied the relationship between knee concentric isokinetic muscle performance and functional joint stability in the dominant and non-dominant limbs of 37 uninjured subjects. Isokinetic muscle performance was defined by hamstrings and quadriceps peak torque and peak torque to bodyweight at $60°\cdot sec^{-1}$ and $180°\cdot sec^{-1}$, and knee functional joint stability was defined by the normalized single-leg hop for distance. Results demonstrated correlations between all variables for the dominant ($r = 0.39 - 0.65$, $P < 0.05$) and non-dominant ($r = 0.49 - 0.69$, $P < 0.05$) limbs.

The relationship between concentric isokinetic muscle performance and knee functional joint stability has also been studied using bivariate correlation methods by multiple research groups in injured subjects. Keays et al.[195] researched the relationship between knee concentric isokinetic muscle performance and functional joint stability in 31 ACL-R subjects with a hamstring autograft. Isokinetic muscle performance was defined by both hamstrings and quadriceps peak torque at $60°\cdot sec^{-1}$ and $120°\cdot sec^{-1}$, and knee functional joint stability was defined by a shuttle run test, a side-step test, the carioca test, the single-leg hop for distance, and the single-leg triple hop for distance. Data showed no correlation between hamstrings isokinetic muscle performance at both velocities and all functional joint stability tests. However, correlations ($r = -0.45 - 0.74$, $P < 0.05$) between quadriceps muscle performance at both test velocities and all functional joint stability tests were identified. Lephart et al.[221] studied the relationship between knee concentric isokinetic muscle performance and functional joint stability in 41 ACL-D subjects. Isokinetic muscle performance was defined by hamstrings and quadriceps peak torque at $60°\cdot sec^{-1}$ and $270°\cdot sec^{-1}$, and knee functional joint stability was defined by the co-contraction test, the carioca test, and a shuttle run test. Results demonstrated no correlation between hamstrings peak torque at both velocities and all three functional tests, or between quadriceps peak torque at both velocities and the co-contraction test and the carioca test. A weak correlation was found between quadriceps peak torque at both velocities and the shuttle run test ($r = -0.41 - -0.42$, $P < 0.05$). Petschnig et al.[294] determined the relationship between knee concentric isokinetic muscle performance and functional joint stability in two groups of ACL-R patients with a bone-patellar tendon-bone autograft: one group was a mean of 12.9 weeks post-surgery and one group was a mean of 53.9 weeks post-surgery. Isokinetic muscle performance was defined by quadriceps peak torque at $15°\cdot sec^{-1}$ and functional joint stability was defined by the single-leg hop for distance, single-leg triple hop for distance, and single-leg vertical hop. Findings showed weak correlations ($r = 0.45 - 0.55$, $P < 0.05$) between all variables for both groups. Sekiya et al.[336] investigated the relationship between knee concentric isokinetic muscle performance and functional joint stability in 107 ACL-R patients with a bone-patellar tendon-bone or hamstring autograft. Isokinetic muscle performance was measured for the hamstrings and quadriceps and knee functional joint stability was defined by the single-leg hop for distance. Data showed weak correlations ($r = 0.22 - 0.25$, $P < 0.05$) between both muscle performance tests and the single-leg hop test. Wilk et al.[388] researched the relationship between knee concentric isokinetic muscle performance and functional joint stability in 50 ACL-R patients. Isokinetic muscle performance was defined by hamstrings and quadriceps peak torque at $180°\cdot sec^{-1}$, $300°\cdot sec^{-1}$, and $450°\cdot sec^{-1}$, and knee functional joint stability was defined by the single-leg hop for distance, the single-leg six meter hop for time, and the single-leg crossover hop for distance. Results revealed weak to moderate correlations ($r = 0.41 - 0.69$, $P < 0.05$) between quadriceps peak torque at all test velocities and all of the hop tests. No significant correlations were reported between any of the hamstrings isokinetic muscle performance tests and any of the hop tests. Based on these bivariate correlation studies, only weak to moderate relationships are consistently identified between hamstrings and quadriceps isokinetic peak torque, and so interventions to positively change isokinetic peak torque may not beneficially change knee functional joint stability.

In addition to bivariate correlation paradigms, it is also clinically useful to determine the proportion that knee isokinetic muscle performance contributes to knee functional joint stability using multivariate regression techniques. Identifying the proportion that knee isokinetic muscle performance contributes to knee functional joint stability potentially aids clinical decision making and the prioritization of interventions. Few research groups have employed multiple regression models to determine the contribution of knee isokinetic muscle performance to knee functional joint stability. Roberts et al.[315] studied the effects of knee laxity, proprioception, and isokinetic muscle performance on knee functional joint stability in 36 ACL-D patients. Predictor variables included ATD side-to-side difference, a summed flexion and extension TTDPM index, and a summed concentric isokinetic hamstrings and quadriceps peak torque index at 60°·sec^{-1}. The outcome variable was the single-leg hop for distance. Statistical analysis demonstrated a significant regression model was generated ($R^2 = 0.52$, $P < 0.01$) of which the peak torque index variable made a significant contribution (Coefficient value = 0.40, $P < 0.01$). Swanik et al.[365] studied the contribution of hamstrings reflex, hamstrings stiffness, hamstrings and quadriceps isokinetic muscle performance, and hamstrings flexibility on knee functional joint stability in 12 ACL-D subjects. Hamstrings reflex latency after an ATD perturbation, hamstrings stiffness, hamstrings and quadriceps peak torque at 60°·sec^{-1}, and hamstrings flexibility were the potential predictor variables. The normalized single-leg hop for distance was the outcome variable. Statistical analyses demonstrated that hamstrings and quadriceps isokinetic muscle performance did not contribute to the final prediction model. Based on the bivariate correlation and regression analyses cited here, concentric isokinetic peak torque of the hamstrings and quadriceps at a variety of different test speeds does not seem to make a consistently strong contribution to knee functional joint stability. The clinical utility, therefore, of tests of hamstring and quadriceps isokinetic peak torque relative to knee functional joint stability is unclear.

2.7.8 Current Evidence for Knee Muscle Force Generating Characteristics: Limitations and Incomplete Knowledge-Base

The existing evidence base demonstrates a wide range of correlation studies reporting the relationship between isokinetic hamstrings and quadriceps peak torque at different testing velocities and knee functional joint stability defined by a variety of single-leg hop tests and double-leg agility tests in uninjured and injured subjects. There are a limited number of regression analyses reporting the contribution of hamstrings and quadriceps peak torque to knee functional joint stability defined by single-leg hop tests. Most correlation and regression studies fail to report the reliability of the tests used to generate the variables included in statistical analyses[142, 294, 315, 336, 388] and so the validity of raw data is questionable. Further, authors employing correlation and regression research designs consistently fail to report any *a priori* power analyses,[142, 294, 315, 336, 388] and so it is possible that many studies are underpowered with regard to the number of subjects tested.

Use of hamstrings or quadriceps peak torque as a variable reflecting reactive force generation may not be appropriate because the generation of peak torque can take a considerable amount of time. For example, the mean TTPT at a test velocity of $60°\cdot sec^{-1}$ is more than twice the mean TTPT at $240°\cdot sec^{-1}$.[174, 395] Thus, the peak torque variable does not give information regarding the timely generation of muscle force which has greater clinical implications with regard to rapid post-perturbation joint stabilization. Lower testing velocities (e.g. $15°\cdot sec^{-1}$, $60°\cdot sec^{-1}$) for determining muscle force generation characteristics also do not reflect the true velocity of knee joint displacements during athletic tasks.[142, 169] In many studies, the ROM employed during testing is from 0° to 90° knee flexion,[294, 315, 336, 388] which does not correspond to and exceeds the 10° to 60° knee flexion ROM that is typically seen at the moment of noncontact knee injuries.[203, 204] Thus, assessment of knee neuromuscular control with isokinetic test parameters that do not match the velocity of joint movement or the ROM observed during specific athletic tasks or injury mechanisms violates the "specificity principle" of muscle performance testing and training.[28, 52, 60, 262] These considerations may explain why current research frequently only demonstrates weak to moderate relationships between knee isokinetic muscle performance and knee functional joint stability defined by single-leg hop tests.

Several limitations are apparent in the design of many correlation and regression studies reporting the association between knee isokinetic muscle performance and knee functional joint stability. This undermines the clinical utility of past research and inhibits the potential development of more effective noncontact knee injury prevention and rehabilitation programs. Further, there do not appear to any published studies exploring the association between hamstrings and quadriceps TTPT, which may be a more useful variable for the investigation of rapid muscle force generating characteristics as a critical component of knee feedback neuromuscular control.

2.7.9 Potential Clinical Applications: Interventions to Modify Knee Neuromuscular Control

If feedforward muscle activity (preactivity) is an important component of knee functional joint stability, and iEMG is a variable that quantifies preactivity, it follows that interventions to modify iEMG as a quantity of local knee muscle preactivity may be clinically valuable for inclusion in noncontact knee injury prevention and rehabilitation programs. To date, there are no published studies that report specific clinical interventions (e.g. balance training, plyometric training) are capable of selectively modifying local knee muscle preactivity quantified by the iEMG variable. There is one study, however, that reports a mixed-mode training program is capable of modifying preactivity iEMG of proximal lower limb muscles considered important for limiting excessive knee valgus displacement. Lephart et al.[217] administered an eight week (× 3 training sessions/week) training program to two groups of female high-school athletes (Basic Resistance Group $n = 13$; Plyometric group $n = 14$) who regularly competed in agility-biased team sports. Preactivity iEMG of the vastus lateralis, vastus medialis, lateral hamstrings, medial hamstrings, and gluteus medius was measured during a jump-landing task before and after the eight week intervention. The basic resistance group performed lower quadrant flexibility, balance, and bodyweight/Theraband strength training exercises. The plyometric group performed the same exercises as the basic resistance group plus plyometric and agility exercises. Following the intervention period, gluteus medius preactivity iEMG was significantly ($P < 0.05$) increased in both groups. A noncontact valgus collapse of the knee is associated with increased hip adduction and internal rotation.[159, 208, 299] The gluteus medius muscle is capable of controlling hip rotations in the adduction and internal rotation directions.[89, 275] Thus, training of the gluteus medius is recommended as part of comprehensive noncontact knee injury prevention intervention programs.[299] Although the work of Lephart et al.[217] did not show a significant enhancement of local knee muscle preactivity iEMG, it does provide good evidence that other lower limb muscles' feedforward activation characteristics can potentially be positively modified with clinical interventions common to the sports medicine environment.

If TTPT is a variable that describes a critical component of knee feedback neuromuscular control and is significantly associated with knee functional joint stability, its measurement and subsequent true clinical value lies in whether it is modifiable with specific clinical interventions. Research examining the ability of specific interventions to modify hamstrings and/or quadriceps

TTPT is scarce. Ihara and Nakayama[176] administered a three month (× 4 training sessions/week) exercise program to patients with knee functional instability. Hamstrings isokinetic TTPT was measured before and after the intervention. Exercises consisted of foot-coordination, roller board, balance board, and perturbation drills. Following the intervention period, TTPT was significantly ($P < 0.01$) reduced. Wojtys et al.[397] administered a six week (× 3 training sessions/week) exercise program to three groups of uninjured subjects: an isokinetic strength training, isotonic strength training, and agility training group. Hamstrings, quadriceps, and plantarflexor isokinetic TTPT was measured before and after the intervention period. No statistically significant differences were identified in TTPT in any of the muscle groups for any of the training programs, although the authors report a trend for TTPT decreases in the isokinetic and agility training groups, with the agility training group improving the most. Based on these two works, there appears to be some evidence that TTPT can be specifically modified with foot-coordination, balance, perturbation, and agility training drills.

2.7.10 Summary

Neuromuscular control is the motor component of sensorimotor control. Neuromuscular control is composed of feedforward and feedback neuromuscular control, and both manifest as the active restraint of excessive joint motion, the coordinated dampening of joint loads, and the facilitation of efficient movement patterns. Feedforward neuromuscular control is the preparatory activation of and force generation by the dynamic restraints before the onset of joint motion and loading. Feedback neuromuscular control is the reactive activation of and force generation by the dynamic restraints after the onset of joint motion and loading. As such, feedforward and feedback neuromuscular control are important for injury prevention and the limitation of tissue damage in noncontact knee injury situations. The association between feedforward and feedback muscle activation characteristics and knee functional joint stability has studied by some research groups, but clear associations between variables have yet to be identified. There is potential for lower limb muscle preactivity to be modified with specific exercise training methods and, therefore, the association between local knee feedforward muscle activation characteristics and knee functional joint stability requires further investigation.

Concentric isokinetic peak torque has frequently been used as measure of neuromuscular control, but consistently demonstrates only weak to moderate associations with knee functional joint stability defined by single-leg hop tests. The timely generation of hamstrings and quadriceps muscle forces and the resulting joint torques is needed if excessive joint displacements are to be rapidly neutralized during a noncontact valgus collapse of the knee. Concentric isokinetic TTPT represents the ability to rapidly and dynamically generate torque, and a reduction in TTPT is considered to be an important goal in noncontact knee injury prevention and rehabilitation programs.[146] There are no published studies investigating the association between isokinetic hamstrings and quadriceps TTPT and knee functional joint stability defined by single-leg hop tests or 3D analysis of dynamic knee valgus. There is potential for hamstrings and quadriceps TTPT to be modified with specific exercise training methods and, subsequently, the association between hamstrings and quadriceps TTPT and knee functional joint stability warrants study.

2.8 METHODOLOGICAL CONSIDERATIONS

This section summarizes subject selection considerations along with the tests, outcome variables, and predictor variables that were employed in this study. Test operational definitions and psychometric properties are presented and the rationale underlying the variable extracted from each test is also be summarized. Outcome and predictor variables are summarized for the reader in Table 1 at the end of this section. The specific procedures for each test are described in detail thereafter in Chapter 3.

2.8.1 Subject Selection and Gender Variable Designation

Noncontact knee injuries are sustained by male and female athletes participating in agility-biased team sports.[40, 208] The mechanism of noncontact knee injury involves a combined movement pattern of knee flexion, knee valgus, ATD, and tibial internal rotation that is commonly experienced by both male and female games players.[203, 204, 209] Therefore, both males and females were recruited for this study. Further, because females can demonstrate statistically significant differences in knee proprioception,[320] neuromuscular control,[29, 153, 174, 218, 320, 341, 392, 401] and biomechanical[64, 88, 118, 218, 341] characteristics when compared to males, gender was included as a variable in statistical analyses with males being designated as the reference group.

Lower limb musculoskeletal injury can result in persistent impairment of lower limb sensorimotor function.[16, 42, 162, 325] Acquired medical pathology (e.g. diabetes) can result in sensorimotor control dysfunction.[376] Subject exclusion criteria, therefore, were: current dominant lower limb pain, any time-loss dominant lower limb injury (i.e. injury requiring withdrawal from one or more sports practice or competition) in the previous two months, any diagnosed knee ligament deficiency (e.g. ACL-D, PCL-D) or meniscal lesion in the dominant limb, or any history of dominant lower limb knee surgery, and any current medical condition that can affect peripheral sensory nerves (e.g. diabetes).

2.8.2 Adapted Crossover Hop for Distance

The adapted crossover hop for distance (Figure 2) was used as a clinical test of knee functional joint stability as previously employed by Clark et al.[73] and Herrington.[156] The adapted crossover hop for distance is a reliable (intraclass correlation coefficient (ICC) (2,1) = 0.94),[73, 156] precise (standard error of measurement (SEM) = 28.8cm),[73, 156] and content valid[73, 74] measure of multi-directional knee functional joint stability. Single-leg hop distance (cm) was extracted from this test as an operational definition and outcome variable representing indirect measurement of knee functional joint stability.

Hop distance is an important variable because multi-directional single-leg hop tests measured by the distance completed during the tests are clinically capable of predicting those who will regain knee functional joint stability defined by patient self-report of return-to-function after knee ligament injury and/or surgical reconstruction.[103, 147, 170, 231] American and European best practice guidelines recommend that single-leg multi-directional hop tests are routinely employed as part of a test battery intended to fully characterize knee functional joint stability.[70, 104, 232, 233, 258] Functional performance tests are clinically important because they indirectly represent the effectiveness of proprioception and neuromuscular control mechanisms to maintain knee functional joint stability by dynamically controlling joint kinematics during the deliberate application of shearing and rotational forces to the knee.[70, 115, 222]

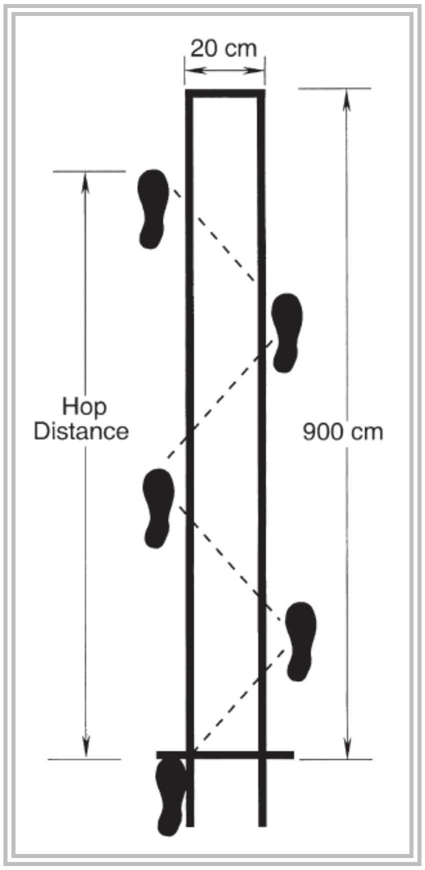

Figure 2. Adapted Crossover Hop for Distance

From: Clark et al.[73]

2.8.3 Single-Leg Stop-Jump

The single-leg stop-jump (Figure 3) was used as a laboratory test of knee functional joint stability as previously employed by Abt et al.,[2] Benjaminse et al.,[31] and Nagai et al.[273] The single-leg stop-jump is a repeatable test for the collection of 3D knee kinematic data,[337] is a high-demand test that simulates sudden deceleration movement patterns specific to agility-biased team sports such as basketball and handball,[31, 273] and is a task that elicits knee valgus kinematics in male and female athletes.[31, 337] Total knee valgus displacement (°) during stance phase will be extracted from this test as an operational definition and outcome variable representing direct measurement of frontal plane knee functional joint stability.

Knee valgus displacement is an important variable when considering knee functional joint stability because a progressive valgus collapse of the knee is the most common mechanism of noncontact knee injury in agility-biased team sports,[203, 204, 208] and represents a direct manifestation of loss of knee joint stability. Stance phase total knee valgus displacement is, therefore, clinically relevant and important because as valgus displacement progresses, ACL and MCL tensile loads also progress to levels capable of causing ligamentous injury.[33, 245, 348]

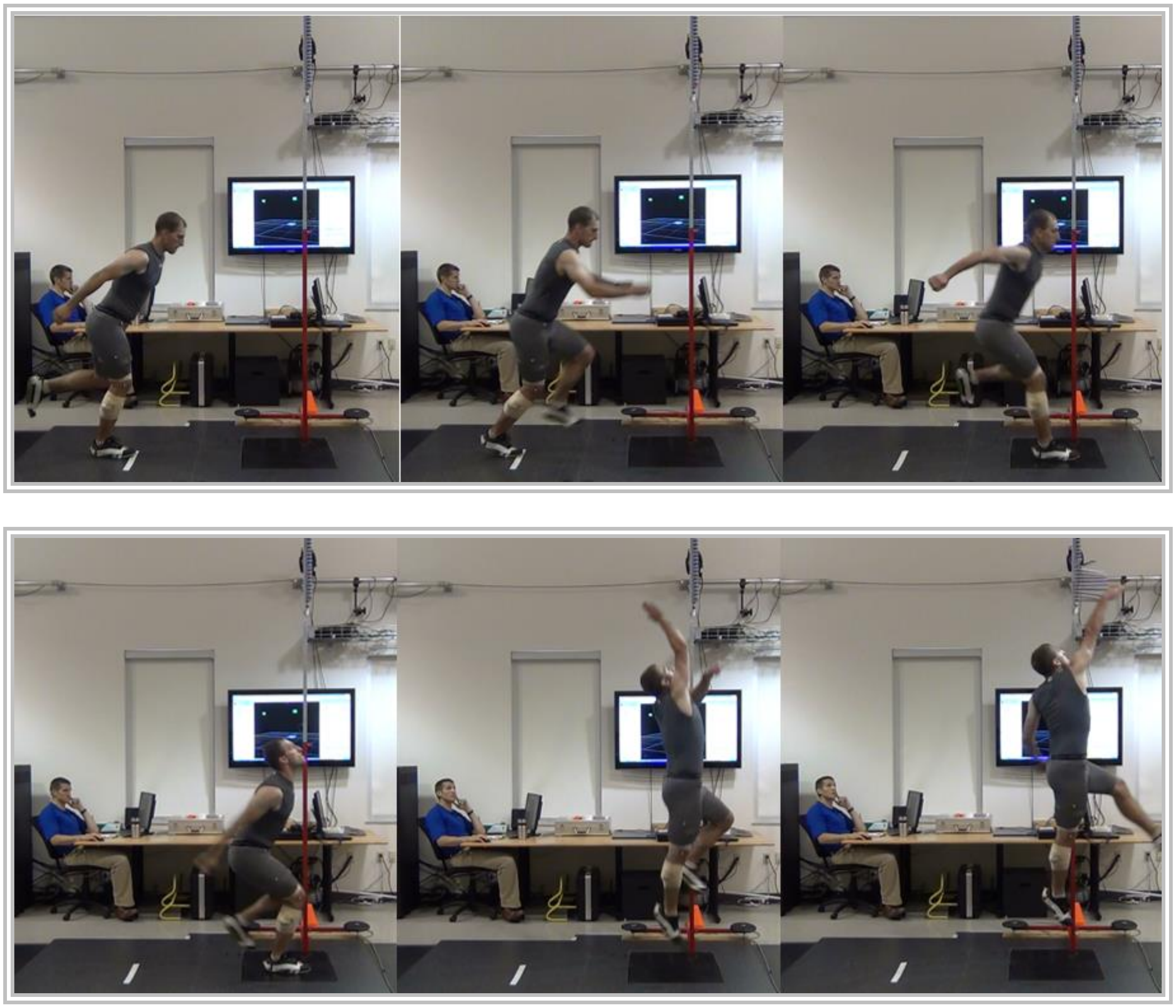

Figure 3. Single-Leg Stop-Jump

2.8.4 Knee Anterior Tibial Displacement

A KT-1000 knee arthrometer (Figure 1) was applied to measure knee mechanical joint stability as previously used by Lephart et al.[221] and Rozzi et al.[320, 321] The manual maximum test was used versus other displacement loads (e.g. 20lb (89N)) since this test has been shown to be the most sensitive procedure for measuring ACL integrity.[80, 81] Pilot testing has established that measurement of ATD with the KT-1000 manual maximum test at 30 ± 5° knee flexion is reliable (*n* = 12; ICC (2,1) = 0.98; SEM = 0.25mm). Previous research has demonstrated that measurement of ATD with the KT-1000 is a valid procedure.[79, 81] Anterior tibial displacement (mm) was extracted from this test as an operational definition and predictor variable representing ACL integrity and knee mechanical joint stability.

The ACL provides a mean of 86% of the total restraining force to straight-plane ATD in the intact human knee at angles above 30° knee flexion, being classed as a primary static restraint to ATD.[56] The ACL also contributes a mean of 15% and 13% of the total restraining force to straight plane valgus displacement in the intact human knee at angle of 5° and 25° knee flexion, respectively, being classed as a secondary static restraint to knee valgus displacement.[148] The ACL, therefore, functions as a clinically significant static restraint for two of the individual movements that compose a dynamic knee valgus collapse (ATD, valgus). Because optimal knee functional joint stability can be considered the final product of mechanical joint stability acting in conjunction with proprioception and neuromuscular control,[19, 70, 115, 185, 280] mechanical joint stability must be measured to understand its contribution to functional joint stability. It is clinically important to objectively measure ATD as a representation of ACL integrity since no valid clinical impression can be formed regarding an individual's knee functional joint stability unless the status of the individual's knee mechanical joint stability is also known.

2.8.5 Knee Active Joint Position Sense

An infrared 3D motion analysis system was used to capture two-dimensional (2D) saggital plane kinematics for the purpose of measuring knee AJPS. Two retroreflective markers defined each segment composing the knee (thigh, shank). Marker placement was modified from previous work:[12, 16, 361] 14mm diameter retroreflective markers were placed over the lateral malleolus, head of fibular, femoral lateral epicondyle, and mid-point between the femoral lateral epicondyle and the greater trochanter. The prone knee extension AJPS test (Figure 4) was used to measure hamstrings-biased eccentric-to-isometric AJPS. Pilot testing has established that this test is reliable (n = 14; ICC (2,1) = 0.86, SEM = 1.3°). Knee AJPS is a valid method for measuring knee proprioception. Prone knee extension absolute error (°) will be extracted from this test as an operational definition and predictor variable representing hamstrings-biased knee proprioceptive acuity.

The prone knee extension test was used to bias the hamstrings because this muscle group is an important local dynamic restraint for the individual movements that compose a dynamic knee valgus collapse (valgus, ATD, tibial internal rotation).[160, 230, 235, 261, 285] The muscle spindle is the most sensitive and potent of all proprioceptors,[129, 139, 319] and so an AJPS test was used to exploit alpha-gamma coactivation and deliberate stimulation of the muscle spindle.[139, 319] Eccentric muscle actions generate the most powerful stimulus for the muscle spindle,[139, 319] and are critical for decelerating joint perturbations.[9, 213, 229] Therefore, an eccentric-to-isometric AJPS test focuses mechanical stimuli on the muscle spindle, as well as simulates the natural sequence of muscle actions observed with dynamic restraint strategies for limiting excessive joint perturbations. An angle of 45° knee flexion was used as the target angle (TA) because: this is a functional knee angle during sports-specific movement patterns;[341, 351] it is an angle that lies within the knee flexion ROM in which noncontact knee injuries occur;[203, 204, 208] it is an angle at which the knee joint capsule, cruciate ligaments, and collateral ligaments are experiencing relatively low tensile loads compared to other points in the knee ROM[107, 326, 371] theoretically resulting in relatively lower inert tissue mechanoreceptor discharge and biasing muscle-tendon proprioceptor stimulation; and antagonist muscle tissue will be relatively relaxed due to avoiding end-ROM stretch thereby negating antagonist muscle (quadriceps) proprioceptor discharge.

Knee AJPS is important to clinical practice because muscle tissue is active which bares more potential clinical relevance to knee functional joint stability than passive tests of knee proprioception. It is potentially important to know the active proprioceptive status of an individual in order to make a clinically relevant impression regarding the contribution of a specific muscle group's proprioceptive apparatus to knee functional joint stability.

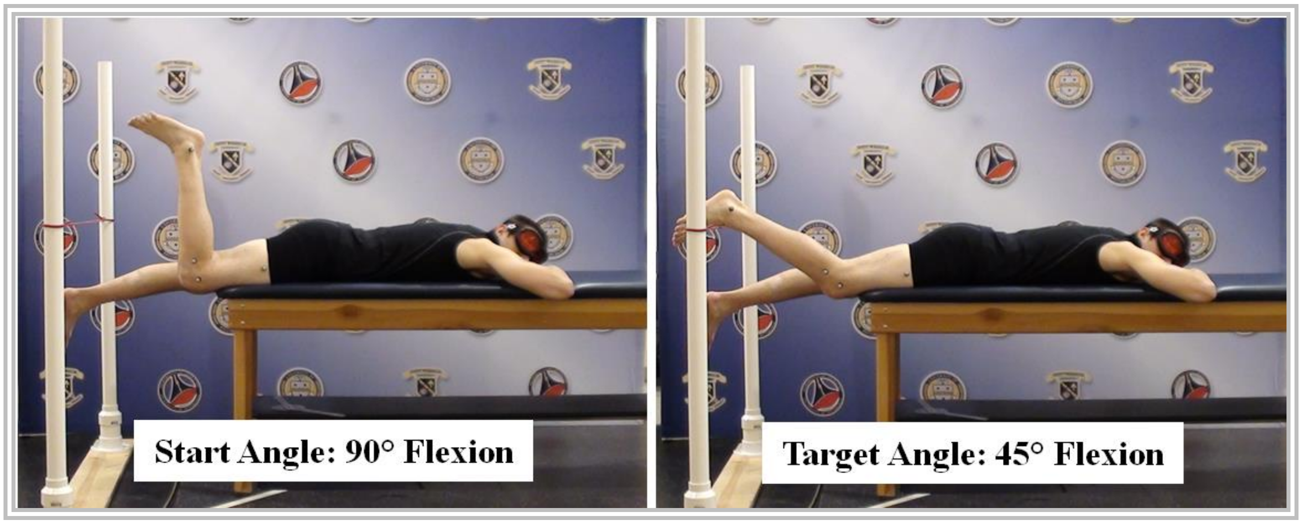

Figure 4. Prone Knee Extension Active Joint Position Sense Test

2.8.6 Maximum Voluntary Isometric Contraction Surface Electromyography

Surface electromyography (sEMG) was used to measure medial hamstrings activation during a single-leg knee flexion maximum voluntary isometric contraction (MVIC). Collection of sEMG data during an MVIC is reliable.[200, 399] Collection of EMG data during an MVIC is a valid means of measuring lower limb maximum voluntary muscle activation in uninjured subjects.[255, 324]

The MVIC was collected at 45° knee flexion because this angle lies within a functional ROM exhibited during sports-specific movement patterns[341, 351] and is also an angle that lies within the ROM in which noncontact knee injuries occur.[203, 204, 208] A five second MVIC was collected as performed in previous work in our laboratory.[337, 341, 342] The mean amplitude of a four second sample (data cropped at points 0.5 seconds after the start and before the finish of the trial) was used as the normalization reference value because previous work has demonstrated mean amplitude to be more repeatable than other methods of normalization (e.g. peak amplitude).[200, 399] The collection of EMG data during an MVIC is important for providing a reference value (100% MVIC) beside which EMG data sampled during a functional task can then be normalized.[200, 358, 374]

2.8.7 Single-Leg Stop-Jump Surface Electromyography

Surface electromyography was used to measure medial hamstrings preactivity and reactivity during the single-leg stop-jump. Preactivity and reactivity represent feedforward and feedback neuromuscular control muscle activation characteristics as previously described by DeMont et al.,[90, 91] Lephart et al.,[217] and Swanik et al.[364, 365] Hamstring muscle sEMG data collection during functional tasks is reliable in our laboratory (ICC (2,1) = 0.98).[356] Surface electromyography is a valid method for determining muscle activation characteristics because it gives a direct representation of reflex and voluntary muscle activation.[24, 310, 374] Surface electromyography is, therefore, a valuable method for closely investigating the dynamic restraint mechanism.[310]

Integrated electromyography was performed following sEMG data collection. Integrated electromyography is a useful method for specifically measuring cumulative muscle activation over a defined timeframe.[24, 137, 391] The unit of measurement used to report iEMG was: percentage of MVIC multiplied by second (%MVIC × sec).[217] Specifically, the %MVIC × sec unit of measurement was used to quantify the medial hamstrings neuromuscular control predictor variables of preactivity and reactivity iEMG.[217] The medial hamstrings were sampled because this muscle group is the most effectively placed to act as a local dynamic restraint for resisting excessive knee valgus displacement.[14, 235, 285] The hamstrings are also the most effectively located dynamic restraints for controlling excessive anterior tibial displacement.[160, 261, 307]

Increased muscle activation results in a proportional increase in muscle stiffness.[119, 120, 186, 257, 353] Muscle stiffness is defined as the ratio of change in muscle force to change in muscle length.[76, 183, 187] Increased muscle stiffness results in greater resistance to lengthening of the muscle-tendon unit.[76, 257, 353] Increased muscle activation and stiffness, therefore, result in enhanced stiffness (stability) of the joint underlying the muscles and greater resistance to joint displacements.[183, 225, 235, 257, 353] Sufficiently activated muscles protect the underlying joint from excessive displacement and shield the joint’s tissues from potentially injurious forces.[183, 185, 225] Surface EMG does not measure muscle force and, consequently, is not a direct measure of muscle stiffness. However, because increased muscle activation results in a proportional increase in muscle stiffness,[119, 120, 186, 257, 353] use of sEMG to measure muscle preactivity and reactivity is clinically important for, theoretically, giving an indirect and yet valuable indication of cumulative muscle stiffness of the dynamic restraints while they are being employed within specific neuromuscular control strategies intended to maintain functional joint stability.

The defined timeframe for measurement of medial hamstrings preactivity was 150msec before initial contact of the single-leg stop-jump task, and for reactivity was 150msec after initial contact.[90, 91, 217, 365] A timeframe of 150msec was used for medial hamstrings preactivity because this timeframe specifically captures feedforward muscle activation primarily initiated by visual inputs to the motor cortex.[166, 331, 332] A timeframe of 150msec was used for medial hamstrings reactivity because this timeframe specifically captures feedback monosynaptic and polysynaptic reflex muscle activation initiated due to joint and muscle afferent inputs to the CNS.[54, 165, 166, 251, 394] Preactivity and reactivity timeframes are clinically important because, together, they contribute to a thorough profile of muscle activation characteristics. This is important for clearly understanding neuromuscular control strategies that are potentially employed for increasing muscle stiffness and maintaining functional joint stability.

2.8.8 Isokinetic Hamstrings Time-to-Peak Torque

Isokinetic dynamometry (Figure 5) was used to measure dynamic time-to-peak torque (TTPT) as a component of feedback neuromuscular control, as previously employed by Rozzi et al.,[320] Vairo et al.,[375] and Wojtys et al.[395, 397] Pilot testing has established that knee flexion (hamstrings) TTPT testing is reliable (*n* = 12; ICC (2,1) = 0.99, SEM = 7.5msecs) when collected during reciprocal extension (quadriceps) and flexion concentric-concentric isokinetic testing at 240°·sec^{-1} in a ROM of 60-0°. Isokinetic dynamometry is a content-valid method for assessing knee muscle performance.[50, 60, 98, 191, 293] Time-to-peak torque (msecs) for the hamstrings was extracted from this test as an operational definition and predictor variable representing local knee muscle reactive force generating characteristics as specific components of knee feedback neuromuscular control.

Knee flexion TTPT was tested as a representation of hamstrings force generating characteristics because this muscle group is a biomechanically effective local dynamic restraint for the individual movements that compose a dynamic knee valgus collapse (valgus, ATD, tibial internal rotation).[14, 160, 178, 230, 235, 261, 285] A test velocity of 240°·sec^{-1} was used because unpublished data (*n* = 30) has revealed the mean peak velocity of knee valgus displacement during the single-leg stop-jump is 244.5 ± 83.3°·sec^{-1}. An arc-of-motion of 60° to 0° knee flexion was used since this is the range of knee flexion in which noncontact knee injuries occur.[203, 204, 208] Consideration for the velocity of isokinetic testing and the arc-of-motion in which testing occurs relative to a functional task is critical for the specificity principle of muscle performance testing to be fulfilled.[52, 60, 262]

Time-to-peak torque is important to clinical practice because the timely generation of force by the dynamic restraints will reduce excessive knee joint displacements and correct knee joint alignment in potential injury situations.[176, 395, 397] Generation of force by the knee muscles increases muscle stiffness, which concurrently increases knee joint stiffness and reduces knee joint displacements following the application of perturbing external forces.[393, 396] Knee TTPT is, therefore, an important variable for consideration in noncontact knee injury control programs.[146]

Figure 5. Isokinetic Knee Extension-Flexion Time-to-Peak Torque

Table 1. Predictor and Outcome Variables

Hypothesis 1	
Predictor Variable	*Outcome Variable*
Gender (Male (0)/Female (1))	Adapted crossover hop for distance mean hop distance (cm)
Mean anterior tibial displacement (mm)	
Prone knee extension active joint position sense mean absolute error (°)	
Isokinetic hamstrings time-to-peak torque (msec)	
Hypothesis 2	
Predictor Variable	*Outcome Variable*
Gender (Male (0)/Female (1))	Single-leg stop-jump mean valgus (−)/varus (+) displacement (°)
Mean anterior tibial displacement (mm)	
Prone knee extension active joint position sense mean absolute error (°)	
Medial hamstrings mean preactivity (preparatory/feedforward muscle activity) (%MVIC × sec)	
Medial hamstrings mean reactivity (reactive/feedback muscle activity) (%MVIC × sec)	
Isokinetic hamstrings time-to-peak torque (msec)	

mm = millimeters; msec = milliseconds; cm = centimeters
MVIC = maximum voluntary contraction; sec = seconds

3.0 METHODS

3.1 STUDY DESIGN

This study utilized a cross-sectional design.[202]

3.2 SUBJECT RECRUITMENT

Ethical approval for this study was acquired from the University of Pittsburgh Institutional Review Board (IRB). Subjects were a sample of convenience recruited via posted flyers around the University of Pittsburgh campus, the University of Pittsburgh Medical Center (UPMC) Center for Sports Medicine, and local locations where the Neuromuscular Research Laboratory was already known to fitness enthusiasts and team sports athletes. Subjects expressing an interest in participating in this study initially telephoned the Principal Investigator who administered a brief telephone screen relative to the inclusion and exclusion criteria in order to determine subjects' eligibility to participate.

3.3 SUBJECT CHARACTERISTICS

3.3.1 Inclusion Criteria

Subjects were included if they were physically active males/females, aged 18-40 years inclusive, where "physically active" was defined as participating in Level II sports or higher according to the Noyes' Knee Sports Activity Rating Scale (Appendix A).[278] Although this scale includes the term "sports" in its nomenclature, the category of Level II sports includes physical activities and movements (running, twisting, turning, jumping, pivoting, cutting) that are also typical components of exercise programs commonly performed by fitness enthusiasts (e.g. circuit training, CrossFit).[386, 387] Therefore, in addition to sports athletes, fitness enthusiasts engaged in training programs that include the physical activities listed under Level II sports were also eligible for this study.

3.3.2 Exclusion Criteria

Subjects were excluded from this study if they possessed current dominant lower limb pain, any time-loss dominant lower limb injury (i.e. injury requiring withdrawal from one or more sports practice or competition) in the previous two months, any diagnosed knee ligament deficiency (e.g. ACL-D, PCL-D) or meniscal lesion in the dominant limb, any history of dominant lower limb knee surgery ever, any current medical condition that could affect peripheral sensory nerves (e.g. diabetes), any current neurological condition that could affect sensorimotor processing at any level of the CNS (e.g. concussion), and any skin allergy to adhesive tape.

3.4 POWER ANALYSIS

An *a priori* power analysis was performed using G*Power 3 statistical software.[55] Anticipating an effect size $R^2 = 0.35$ ($f^2 = 0.54$) would be generated by a final model that included six predictor variables (Table 1) a minimum of 33 subjects were required to achieve a desired statistical power level of at least 0.80 at a two-sided $\alpha = 0.05$. To the author's knowledge there were no previous multivariate studies employing the combined predictor and outcome variables outlined in this study. Therefore, an $R^2 = 0.35$ was selected as a plausible and expected effect size relative to the single-leg stop-jump as a test for knee functional joint stability because past work consistently demonstrates the knee contributes 45% to 56% of the combined hip-knee-ankle performance during vertical-biased functional tests.[168, 237, 402]

3.5 INSTRUMENTATION

3.5.1 Universal Baseline Goniometer

A 12 inch Universal Baseline Goniometer (Aircast, Summit, NJ) was used to set the knee angle for the knee active joint position sense (AJPS) test and confirm the knee angle for the knee arthrometer test. The Universal Baseline Goniometer is a commonly used device with a resolution of 1° and has frequently been employed for measuring joint angles and knee passive and active ROM in both clinical and laboratory research.[34, 302, 316]

3.5.2 Range-of-Motion Stop

An 'H-frame' (Figure 6) was constructed where the uprights were formed by two PVC pipes inserted into separate wooden bases, and the crossbar was formed by red Thera-Band Tubing (Hygenic Corporation, Akron, OH) secured with firm tension. This frame functioned as a ROM guide when cueing subjects to the knee AJPS test's target angle.

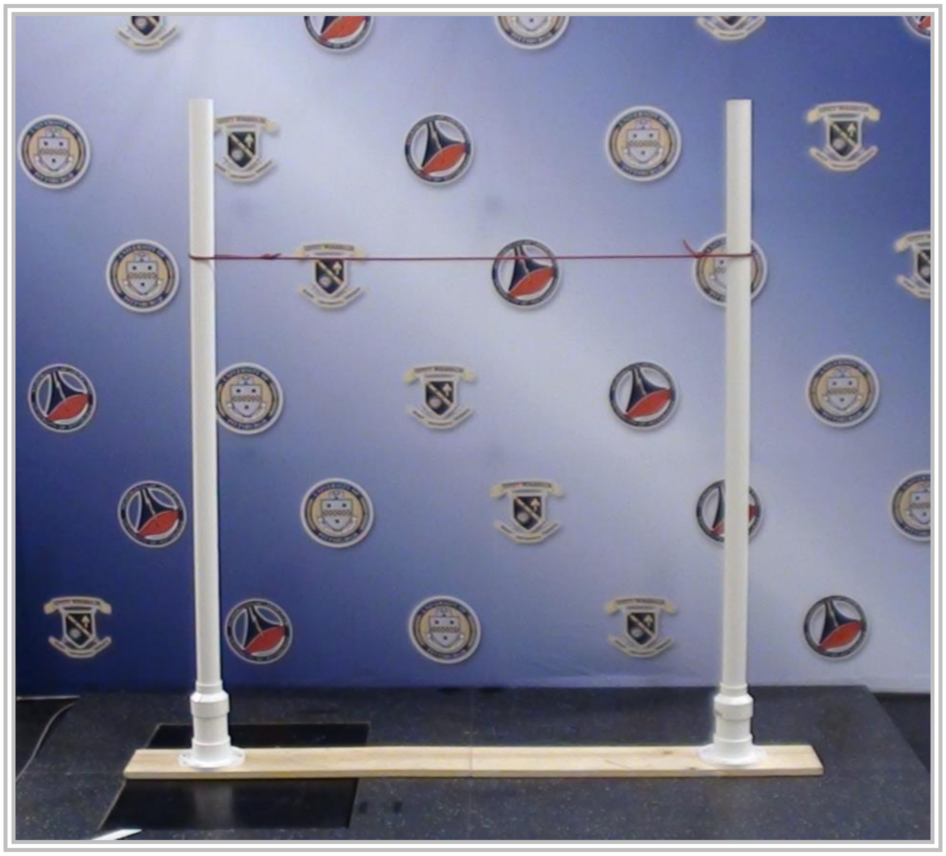

Figure 6. H-Frame Range-of-Motion Stop

3.5.3 Knee Arthrometer

Knee anterior tibial displacement (ATD) was measured using a KT-1000 Knee Ligament Arthrometer (MEDmetric Corporation, San Diego, CA)[253] calibrated according to the manufacturer's guidelines. The KT-1000 is a well-recognized research device with a resolution of 0.5mm and has been frequently utilized in past knee studies for quantifying saggital plane (anteroposterior) knee mechanical joint stability.[221, 320, 321]

3.5.4 Anthropometer and Anthropometric Tape Measure

A Model 01291 Anthropometer (Lafayette Instrument Compnay, Lafayette, IN) and a Baseline Anthropometric Tape Measure (Aircast, Summit, NJ) were used to measure selected body and segment dimensions in order to facilitate limb segment model construction prior to data collection during the single-leg stop-jump.

3.5.5 Motion Analysis System

Knee AJPS and 3D kinematics during the single-leg stop-jump were measured using the Vicon Nexus passive digital video-based motion capture system synchronized with eight MX13 infrared light emitting high-speed cameras (Vicon Motion Systems, Centennial, CO).[380] Six cameras were wall-mounted and two were free-standing on their own robust tripods. All cameras were strategically placed and aimed at the center of the motion capture area. The motion capture area had a capture volume of 240cm long × 150cm wide × 150cm high. Calibration was performed according to the manufacturer's guidelines using a manual wand calibration procedure: as recorded by the software display calibration to a root-mean-square (RMS) of 0.20 was accepted. The Vicon Nexus motion capture system has a reported accuracy of 117μm when configured with 14mm diameter Vicon retroreflective markers and a manual system calibration.[390] Data was sampled at 250Hz. The Vicon Nexus motion system has frequently been employed in past knee studies for capturing 3D knee kinematics during hopping, jumping, and landing maneuvers.[31, 67, 340]

3.5.6 Force Plate System

Initial contact during the first landing of the single-leg stop-jump was identified using a KISTLER 9286A force plate (KISTLER, Amerhurst, NY)[198] embedded in a custom-made surround platform. The KISTLER 9286A force plate is a multicomponent system including four three-component piezoelectric force transducers housed in an aluminum top plate. One transducer is mounted in each corner of the top plate, each transducer with a lower detection threshold of 10 milliNewtons. Data was sampled at 1500Hz. The KISTLER force plate is a popular device in lower limb investigations involving the sampling of ground reaction forces during hopping, jumping, and landing maneuvers.[31, 338, 340]

3.5.7 Surface Electromyography System

Muscle activity was collected using Ambu® Blue Sensor N rectangular (30mm × 22mm × 1.6mm) silver-silver chloride, active, bipolar, pre-gelled, self-adhesive surface electrodes (Ambu®, Denmark)[11] and a Noraxon TeleMyo DTS multi-channel telemetric surface electromyography (sEMG) system (Noraxon USA Inc., Scottsdale, AZ).[276] This 16-bit resolution system has an input range of ± 3.5mV and is composed of self-contained ultra-light (approximately 14 grams) sEMG sensor transmitter units, a belt receiver unit, and a Noraxon 2400R G2 Analog Output Receiver unit. Data was sampled at 1500Hz. All sEMG signals were passed through a single-end 500-gain amplifier and a 10-500Hz low-pass filter within the self-contained, ultra-light Noraxon TeleMyo DTS sensor units. The sensor units transmitted signals to the belt receiver unit, which then transmitted signals to the Noraxon Analog Output Receiver unit. Raw sEMG signals were passed from the Analog Receiver Unit to a 32-channel 24-bit analog-to-digital (A:D) board (Model DT3010, Data Translation Inc., Marlboro, MA) for conversion from analog to digital form.

3.5.8 Visual Target

A visual target and motivational tool for the vertical component of the single-leg stop-jump maneuver was provided by the VERTEC Jump Trainer (Sports Imports, Columbus, OH).[377] The VERTEC is a well-recognized testing tool with a resolution of 0.50 inches (1.27cm), and has been utilized by many authors employing single-leg vertical jumping maneuvers in various knee research studies.[250, 311, 366]

3.5.9 Isokinetic Dynamometer

Hamstrings time-to-peak torque (TTPT) was measured with a Biodex System 3 PRO isokinetic dynamometer (Biodex, Shirley, NY).[36] This isokinetic dynamometer is a popular knee muscle testing tool with a resolution of 10.0 msec for TTPT and has been employed in multiple research studies investigating various aspects of knee function.[8, 273, 339]

3.6 PROCEDURES

All testing was performed at the University of Pittsburgh Neuromuscular Research Laboratory (NMRL). Subjects reported to the NMRL for one test session lasting up to a maximum of two hours and 15 minutes. The inclusion and exclusion criteria documented during the telephone screen were reviewed to confirm subjects' study eligibility. After this subjects completed the Noyes' Sports Activity Rating Scale (Appendix A)[278] to verify habitual physical activity levels. Subjects then read and signed an Informed Consent approved by the University of Pittsburgh's IRB. Prior to testing, all instrumentation was carefully prepared and calibrated according to the manufacturers' recommendations.

Testing was performed in a quiet laboratory space to avoid subject distractions and that was environmentally controlled (70-75°F; 25-50% humidity) to ensure physiological homeostasis. Subjects undertook sufficient familiarization trials within each specific test to "prime" the nervous system and saturate acute learning effects.[37, 45, 298]

Specific test order was considered with regard to negating the potential effects of repeated trials of the knee during arthrometer testing on subsequent proprioceptive measures. Consideration was to stabilize acute connective tissue hysteresis and muscle thixotropy effects that could affect and confound proprioceptive acuity over repeated movements.[144, 300] Tests were progressed from "high-skill" to relative "low-skill" tasks to attenuate the cumulative effects of progressive peripheral muscle fatigue.[151, 152, 389] A specific test order was performed for each subject. Test order was: Noyes' Knee Sports Activity Rating Scale, Informed Consent, AJPS, ATD, dynamic warm-up, adapted crossover hop for distance, sEMG preparation, knee flexion maximum voluntary isometric contraction (MVIC), single-leg stop-jump, and isokinetic hamstrings TTPT.

The dominant leg of all subjects was tested as performed in past knee sensorimotor control research where the dominant leg was operationally defined as the preferred kicking limb when kicking a soccer ball.[2, 218, 338] Subjects wore athletic shirts and spandex shorts for all physical tests. For the AJPS and ATD tests subjects were barefoot. Subjects were blindfolded for the knee AJPS tests.[57] For the dynamic warm-up, adapted crossover hop for distance, single-leg stop-jump, and isokinetic test, subjects also wore their preferred athletic shoes.

3.6.1 Noyes' Knee Sports Activity Rating Scale

The Noyes' Knee Sports Activity Rating Scale[278] (Appendix A) was used to operationally define and measure physical activity for this study. The scale is a quick-and-easy to complete questionnaire that demonstrates reliability (ICC > 0.70), construct validity, and discriminative validity.[18]

3.6.2 Knee Active Joint Position Sense

Prone knee extension AJPS was collected as an operational definition of knee proprioception for this study. An angle of 45° knee flexion was used as the target angle (TA).[42, 57, 325] In pilot testing, the prone knee extension test (Figure 4) demonstrated reliability (ICC (2,1) = 0.86; SEM = 1.38°) for eccentric-to-isometric hamstrings-biased AJPS.

Marker placement consisted of 14mm diameter retroreflective markers (Vicon Motion Systems, Centennial, CO) placed over the lateral malleolus, head of fibula, femoral lateral epicondyle, and the mid-point between the femoral lateral epicondyle and greater trochanter. Two markers defined each segment for 2D motion capture in the saggital plane only. Markers were secured with double-sided adhesive tape. Four Vicon MX13 infrared cameras were positioned lateral to the subject to create a sufficient capture volume to record 2D saggital plane motion. Knee joint angles were defined as rotation of the distal segment relative to the fixed proximal segment.

Subjects were in prone lying with the hands resting under the head and the head turned sideways resting on the hands. The most lateral aspect of the thigh was aligned with the lateral edge of the treatment table, and the proximal edge of the patella was approximately 5cm off the end of the treatment table to minimize cutaneous cues.[325] Prior to the actual test trials, the TA was established using the Baseline Universal Goniometer. The goniometer axis was aligned with the femoral lateral epicondyle, the stationary arm aligned with the femoral greater trochanter, and the moving arm aligned with the lateral malleolous. Measurement of knee ROM using a 360° universal goniometer is reliable (ICC > 0.90).[49, 69]

In prone, subjects were instructed to actively flex the test knee and a position of 90° knee flexion was assumed - this was the start angle (SA). From this position, subjects were cued to slowly allow the knee to extend by lowering the shank with gravity until a position of 45° knee flexion was acquired - this was the TA. The H-frame was then be placed to ensure the subject moved to the same TA for all TA trials, being carefully positioned so that a point level with the anterior ankle joint line just touched the Thera-Band Tubing (Figure 7). Because the Thera-Band Tubing is a non-rigid structure the subject was unable to rest the leg against the crossbar and relax the hamstrings. When subjects were asked to reproduce the TA (designated the ‘reproduced angle’ (RA)) one of the uprights and its separate base was moved aside so that subjects could no longer touch the Thera-Band Tubing and gain cutaneous feedback.

Figure 7. Ankle-Tubing Configuration During Prone Knee Extension Active Joint Position Sense Target Trials

Prior to every test sequence, subjects actively extended and flexed the knee 10 times through a 90-0° arc of motion. After this, the following sequence was performed:

1. subjects were instructed to "slowly and smoothly" move from the SA to the TA, press the Vicon trigger at the TA to mark that point in the data, and hold the TA for five seconds. When holding the TA verbal instructions included: "Keep holding your leg there… concentrate on feeling where your leg is in space… keep holding your leg there".
2. subjects were then instructed to return to the SA for five seconds
3. subjects were then asked to reproduce the TA and press the Vicon trigger when they felt they had done so
4. the RA was recorded
5. the difference (°) between the TA and RA was calculated and designated the absolute error (AE)[30, 57, 361]

Subjects repeated steps 1 - 5 as above for five cycles (i.e. five TA trials and five RA trials). For each RA trial, subjects were not permitted to “find” the TA by extending and then flexing the knee, since the flexion phase would represent a concentric hamstrings action. Attempted reacquisition of the TA was performed in a single smooth extension movement to ensure eccentric-only hamstrings activity. If subjects did extend and then flex the knee the trial was discarded and repeated. The mean AE (°) from the five cycles was used for data analysis.

3.6.3 Knee Anterior Tibial Displacement

Knee ATD was measured with the KT-1000 arthrometer. In pilot testing, the KT-1000 demonstrated reliability (ICC (2,1) = 0.98; SEM = 0.25mm) for estimating ACL integrity and ATD when using the manual maximum test at 30 ± 5° knee flexion. Knee ATD testing was performed as described by Daniel et al.[81] and the KT-1000 manufacturer’s procedural guidelines.[253]

Subjects were supine lying with head supported, hands resting on abdomen, and eyes closed. A posterior sag test[241] was first performed to screen for PCL deficiency. The subject’s legs were positioned on the thigh support platform with the platform proximal to the popliteal fossa and the knees in 30 ± 5° flexion. The subject’s feet were positioned on the foot support platform so that the lateral aspect of the foot rested against the platform upright and the most inferior aspect of the lateral malleolus was just proximal to the edge of the platform upright. The subject’s legs were positioned in 15 ± 5° external rotation so that the patella faced anteriorly. A check was then made that the patella was fully engaged in the femoral trochlea by applying a gentle medial and lateral glide to the patella. Confirmation the knees were in 30 ± 5° knee flexion was performed with a goniometer aligned over the lateral tibiofemoral joint line. For consistency, the thigh restraint strap was applied to all subjects just distal to the thigh support platform and proximal to the popliteal fossa.

The KT-1000 was applied to the subject's leg so that the long axis of the patellar sensor pad was aligned with the center of the patellar and the joint line arrow was aligned with the tibiofemoral joint line. The KT-1000 was then secured using the distal Velcro strap, the device alignment checked once more and then the proximal Velcro strap was secured. Next a check was made that the subject's muscles were relaxed by palpation of the quadriceps and hamstrings muscle bellies and tendons. Gentle anteroposterior tibiofemoral oscillations were applied where necessary to facilitate muscle relaxation.[81, 253]

The patellar sensor pad was firmly pushed posteriorly so that the patellar was locked in the femoral trochlea and there was no movement on the displacement dial. The displacement dial was then set to zero. Next the tissues were conditioned[253] by applying an 89N anterior force followed by an 89N posterior force: this cycle was repeated until a reproducible static position (± 0.5mm) was obtained at the release of each cycle.[81, 253] The displacement dial was again zeroed without moving the patellar sensor. Next, an 89N posterior force was repeatedly applied and released until the displacement dial returned to the same position three times: when this occurred this was test reference position from where all recorded measurements were performed.[81, 253] The displacement dial was once more zeroed without moving the patellar sensor.

With the patella still locked in the femoral trochlea and the patellar sensor held still, the tester's moving hand was placed on the subject's posterior calf so that the first web space was level with the long axis of the tibial sensor, and a manual maximum test was performed. Care was taken to apply the line of force parallel with the joint line arrow and the long axis of the patellar sensor. Physiological knee extension was prevented so that only ATD occurred. The precise test sequence was:

1. an anterior force was applied until a firm end-feel was felt and no more needle movement was seen on the displacement dial
2. the measurement was read to the nearest 0.5mm
3. an 89N posterior displacement force was applied
4. the displacement dial returned to 0.0 ± 0.5mm.

Steps one to four were repeated so that three measured trials were performed, the mean used for data analysis.

3.6.4 Dynamic Warm-Up

A dynamic warm-up was performed before the adapted crossover hop for distance test. The content of the warm-up was in line with current research[163] and best practice recommendations,[51] and included the following exercises in order over a 2 × 10m distance: toe walking, heel walking, 10 bodyweight parallel squats, forward lunge walk, backward lunge walk, right lateral lunge walk, left lateral lunge walk, high knee lifts, butt kicks, and 10 test leg single-leg squats.

3.6.5 Adapted Crossover Hop for Distance

The adapted crossover hop for distance (Figure 2) was used as a clinical operational definition of knee functional joint stability. The adapted crossover hop for distance demonstrates reliability

(ICC (2,1) = 0.94; SEM = 28.8cm).[73, 156] Prior to performing the adapted crossover hop for distance, subjects were instructed in the standardized dynamic warm-up described previously.

A 1200cm × 20cm course was marked on the laboratory floor (Figure 2). Subjects stood on the target leg with the most distal aspect of the foot in alignment with the 'start line'. The lateral border of the foot was aligned with the contralateral edge of the course (e.g. if right leg was tested, the right foot was in alignment with the left edge of the course, Figure 2). The contralateral knee was flexed to ≈ 90°, the hip in neutral. Subjects executed four consecutive hops obliquely crossing the course with each hop in an attempt to achieve the maximum possible linear displacement from the start line. Arm use was permitted to maintain balance, and subjects were instructed to "stick" the landing from the final hop and maintain single-leg balance. Loss of balance or foot contact with the course voided the trial and resulted in another attempt. Sufficient practice trials were followed by three measured trials in centimeters (cm), each measured trial separated by a maximum 60 second rest period. The mean of the three measured trials was used for data analysis.

3.6.6 Surface Electromyography

Surface electromyography (sEMG) was performed on the medial hamstrings muscle group to collect preparatory and reactive muscle activity during the single-leg stop-jump task. Hamstring muscle sEMG data collection during functional tasks demonstrates reliability in our laboratory (ICC (2,1) = 0.98).[356] Surface electrode placement was modified from the SENIAM (Surface Electromyography for the Non-Invasive Assessment of Muscles) Project guidelines.[343]

Based on the SENIAM project guidelines, subjects were prone, the hip passively internally rotated ≈ 15°, and the ankle resting on a bolster with the knee flexed approximately

20°. To correctly place the electrodes, a point was first marked 50% of the distance between the ischial tuberosity and the medial epicondyle of the tibia. Subjects then actively flexed the knee to approximately 45° and internally rotated the lower leg to increase the prominence of the muscle group. Because each subject's muscle anatomy can be subtly different and the medial hamstrings are consistently more prominent in the proximal direction, a second point was then marked approximately 2.5cm proximal to the first point and used as the site for (mid-point between) the two surface electrodes. To minimize signal resistance caused by the skin, the electrode site was shaved when necessary with a commercial electric razor, abraded using a low-abrasion cosmetic emery board until a light erythema was visible, cleaned with a 70% isopropyl alcohol medical wipe, and allowed to air dry.[24, 137, 343] The electrodes were placed immediately adjacent to each other to yield an inter-electrode distance of 20mm.[341-343] To minimize cross-talk, the electrodes were meticulously aligned parallel with the muscle fibers in the mid-line of the muscle belly (Figure 8a).[24, 85] The sEMG sensor units were attached to the electrodes using snap-on connector studs and then secured to the skin adjacent to the electrodes using commercially available double-sided adhesive discs. Care was taken to ensure both the electrode-sensor connector cables were not twisted or overlapped to minimize potential signal noise induced by cable motion artifacts.[24, 137] To minimize potential signal noise induced by electrode-skin interface, connector stud interface, or sensor-skin interface motion artifacts, the electrodes, connector studs, and sensor units were further secured using Transpore® tape (3M, St Paul, MN) (Figure 8b). A separate ground electrode was not necessary because each sEMG sensor transmitter unit grounded itself. A sub-maximal manual muscle test was performed with real-time visual inspection of the electromyogram to confirm secure electrode placement, integrity of the sEMG signal, and the absence of motion artifacts.[24, 93, 358] The thigh was then wrapped with athletic foam underwrap to provide continued pressure on the surface electrodes to further ensure good electrode-skin contact[24] during the single-leg stop-jump task and protect the entire electrode-sensor unit configuration (Figure 8c).

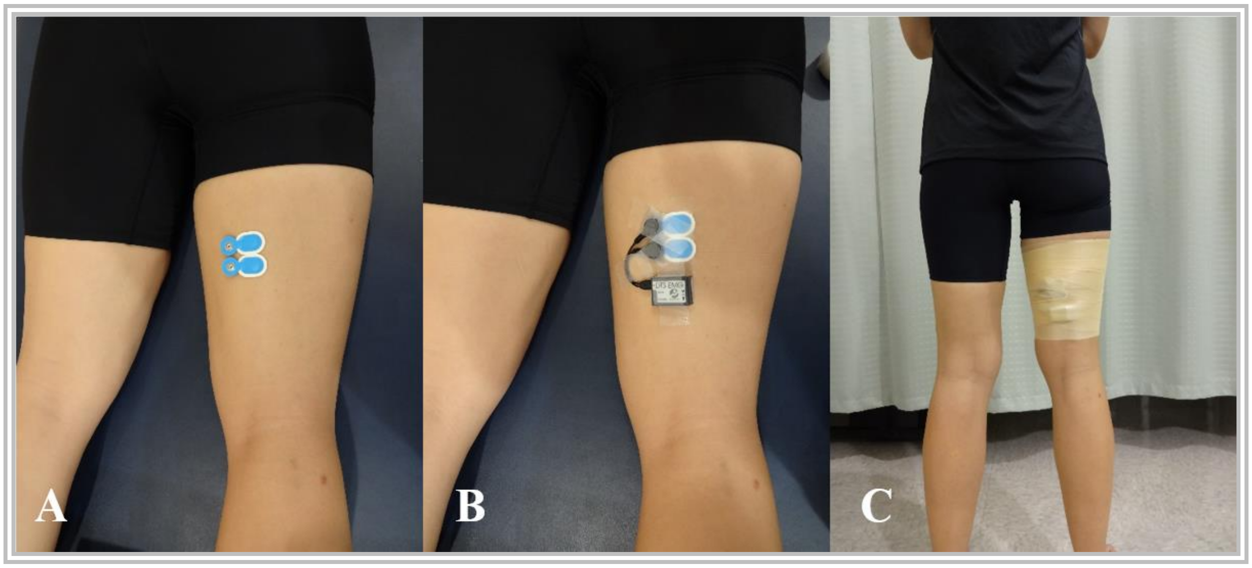

Figure 8. Medial Hamstrings Electrode Placement and Fixation

A five second knee flexion maximum voluntary isometric contraction (MVIC) was collected for normalization of medial hamstrings preparatory and reactive muscle activity during the single-leg stop-jump task.[180, 217, 254, 341, 342] Subjects were positioned in the Biodex dynamometer according to the manufacturer's guidelines. Subjects were seated on the dynamometer with the popliteal fossa approximately 5cm off the edge of the chair and the lateral epicondyle of the target knee aligned with the axis of rotation of dynamometer arm (Figure 5). The torso, pelvis, and target leg were firmly secured using the device's straps. The dynamometer's knee testing attachment was adjusted so the lower edge of the shank strap was just above the proximal margin of the medial malleolous. The MVIC test was performed at 45° flexion. The dynamometer's ROM computer display was used to first set subjects' 0° position (0° passive knee extension) and then set the 45° flexed position. Subjects were given a "3, 2, 1, Go!" countdown after which they were given strong verbal encouragement to "Bend the knee as hard as you can… keep pulling… keep pulling". Real-time and immediate post-collection visual inspection of the electromyogram was again performed to confirm secure electrode placement, integrity of the sEMG signal, and the absence of motion artifacts.[24, 93, 358]

3.6.7 Single-Leg Stop-Jump

The single-leg stop-jump (Figure 3) was used to collect total knee valgus displacement data as a laboratory operational definition of knee functional joint stability. The single-leg stop-jump is a high-demand test that simulates sudden deceleration movement patterns specific to agility-biased team sports such as basketball and handball, and is a functional task that elicits knee valgus motion patterns in male and female athletes.[31, 337] Medial hamstrings sEMG data was also collected for calculation of preparatory and reactive muscle activity.

Measurement of subjects' femoral epicondyle breadth, malleolar breadth, and ASIS-medial malleolus leg-length was performed to facilitate later estimation of joint centers and the construction of the subject-specific biomechanical model.[378, 379] Sixteen 14mm diameter retroreflective markers were placed bilaterally on anatomical landmarks according to the Vicon Plug-In Gait model (Vicon Motion Systems, Centennial, CO) and previous work:[67, 340, 378, 379] the ASIS, posterior superior iliac spine (PSIS), femoral lateral epicondyle, lateral malleolous, posterior calcaneus, and dorsal second metatarsal head, as well as the lateral thigh and lateral shank (Figure 9). Markers were secured with double-sided adhesive tape.

Figure 9. Plug-In Gait Retroreflective Marker Placement

Camera calibration and definition of the Cartesian origin and global coordinate system was performed according to the manufacturer's instructions. A standing static trial in a T-pose with the arms abducted to 90° was captured to serve as the reference position from which dynamic joint angle calculations were performed. Care was taken to ensure subjects' lower limbs were in the anatomical position. The static trial was digitized to define limb segment boundaries, joint locations, and local (segmental) coordinate systems, and enable a subject-specific biomechanical model to be constructed to define the position and orientation of each segment.[378, 379]

Subjects stood on the target leg at a distance equal to 40% of standing height away from the edge of the force plate (Figure 3).[31, 273, 337] The VERTEC was positioned to the side contralateral to the target leg (e.g. if the right leg was tested, the VERTEC was placed to the left side of the subject), immediately adjacent to the force plate, and acted as a visual target for the vertical jump part of the task. Subjects were given a "3, 2, 1, Go!" countdown and executed a single-leg horizontal jump onto the force plate, after which, without any pause, they immediately executed a maximum effort single-leg vertical jump (Figure 3). Arm movement was unrestricted to aid in maintenance of dynamic balance as would occur in actual sports performance and so subjects could strike the vanes of the VERTEC with their dominant hand. A verbal description and visual demonstration of the task was provided. Verbal cues were kept to the minimum necessary to facilitate subjects' successful gross performance of the task without specific modification of individual movement patterns. Sufficient practice trials were followed by three measured trials,[273] each separated by a maximum 60 second rest period. Surface EMG, kinematic, and force plate data collection started and ended approximately one second before and after each measured trial. If the subject failed to land on the force plate or correctly perform the single-leg vertical jump, then the trial was discarded and repeated. Electromyograms and slow-motion digital videos (kinematic and kinetic data) were visually inspected immediately after each trial to ensure clean data collection.

3.6.8 Isokinetic Hamstrings Time-to-Peak Torque

Knee flexion isokinetic dynamometry was used to collect hamstrings TTPT as a measure of feedback neuromuscular control force generating characteristics. Subjects were again configured with the Biodex dynamometer according to the manufacturer's guidelines, after which all isokinetic testing procedures were performed at a velocity of $240°\cdot sec^{-1}$ in a ROM of 60-0°. In pilot testing, knee flexion TTPT measurements at a velocity of $240°\cdot sec^{-1}$ in a ROM of 60-0° demonstrated reliability (ICC (2,1) = 0.99, SEM = 7.5 msecs).

Subjects were seated on the dynamometer as described previously for the knee flexion MVIC test. Range-of-motion limits were set to allow a 60-0° arc-of-motion, the limb weighed, and the subject instructed to extend and flex the knee with no resistance to ensure correct subject-dynamometer configuration. Subjects performed five sub-maximal warm-up trials at 50% perceived maximum voluntary velocity (MVV) immediately followed by five further warm-up trials at 100% MVV. Subjects were provided with 60 seconds rest, given a "3, 2, 1, Go!" countdown, and instructed to perform five reciprocal extension-to-flexion measured trials at 100% MVV from a 60° knee flexion starting position. Verbal instructions included: "Kick out as fast as you can… pull back as fast as you can".[327] Trials were reciprocal concentric-concentric efforts. Gravity correction was automatically performed by the device's software (Biodex Advantage Software v.3.0, Shirley, NY). A text file generated by the software was reviewed to verify subjects achieved a test velocity of $240 \pm 5°\cdot sec^{-1}$ and a ROM of 60 ± 5° to 0 ± 5°. The knee flexion TTPT (msec) from the computer report was used for data analysis.

3.7 DATA REDUCTION AND STATISTICAL ANALYSIS

3.7.1 Data Reduction

For the knee AJPS tests, 2D kinematic data was collected using a custom-designed template in the Vicon Nexus software. The template was built to consist of a simplified two-segment model where the proximal segment represented the thigh and the distal segment represented the shank: the two markers placed on each segment were used to create vectors that defined each segment, the angle in space between the thigh and the shank (the knee joint angle) measured by calculating the dot product of the vectors.[181] Marker trajectories were smoothed within the Vicon Nexus software using a cross-validation Woltring filter.[398] Data was exported from the Vicon Nexus software in text file format and saved on the personal computer. Data was then processed with a custom script in Matlab R2012a (The Mathworks, Natick, MA) using the following steps: the angle recorded at the moment the Vicon trigger was pressed during the target angle trial was identified; the angle recorded at the moment the Vicon trigger was pressed during the reproduction angle trial was identified; the difference between the target angle and the reproduced angle was calculated; data were output for each trial as absolute error values. Specifically, knee flexion angles were calculated using the equation:[181]

$$\theta = \cos^{-1} \left((V1 \cdot V2) \cdot (|V1|\,|V2|)^{-1} \right)$$

where θ was the knee flexion angle, $V1$ and $V2$ were the vectors for the thigh and shank segments relative to the origin, and $|V1|$ and $|V2|$ were the magnitudes of the vectors. Knee flexion angles were described as rotation of distal segment relative to proximal segment in the saggital plane.

For the single-leg stop-jump test, all kinematic, kinetic, and sEMG data recordings were performed using the Vicon software. Prediction of hip, knee, and ankle joint centers was performed by the software using the Vicon Plug-In Gait model.[378] The Vicon Plug-In Gait model predicts hip, knee, and ankle joint centers using marker locations and the previously collected anthropometric parameters according to the work of Davis et al.[82] and Kadaba et al.[189] The thigh segment is created by a vector joining the knee joint center to the hip joint center and the shank segment is created by a vector joining the ankle joint center to the knee joint center. The local knee coordinate system is embedded (Figure 10) by the Vicon Nexus software using the center of the knee joint as the origin, and then 3D joint coordinates incorporating relative Euler (Cardan) rotation angles are reconstructed.[378] Joint angles are described as rotation of distal segments relative to proximal segments. The measurement of knee valgus (−)/varus (+) occurs in the plane created by the knee flexion axis (formed by a line joining the knee joint center and the femoral lateral epicondyle marker) and the ankle joint center.[378] The valgus (−)/varus (+) angle is calculated using the long axis of the shank relative to the long axis of the thigh projected onto this plane.[378] Marker trajectories were smoothed within the Vicon Nexus software using the cross-validation Woltring filter.[398] Initial contact was defined as when the vertical ground reaction force first exceeded 5% of subjects' bodyweight.[67, 340] Kinematic and kinetic data were exported from the Vicon Nexus software in text file format and saved on the personal computer.

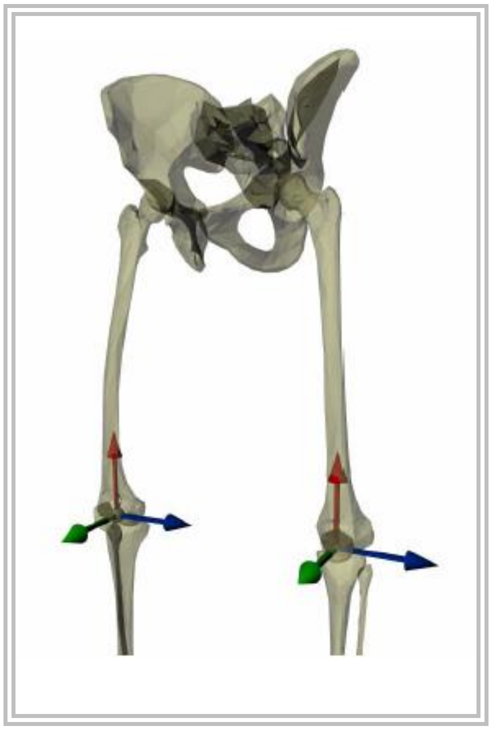

Figure 10. Local Knee Coordinate System

From: Vicon Motion Systems[378]

Green = *x* axis; Blue = *y* axis; Red = *z* axis

Peak knee valgus angle (PKVA) was defined as the highest knee valgus angle recorded between initial contact (IC) and the highest knee flexion angle. Total knee valgus displacement (TKVD) was calculated as: TKVD = PKVA – initial contact knee valgus angle.

All raw sEMG data was exported from the Vicon Nexus software in text file format for signal processing using a custom script in Matlab R2012a. Data were full-wave rectified and low pass filtered using a Butterworth fourth-order zero-phase shift filter with a cut-off frequency of 12Hz.[86, 341, 342] For the five second MVIC trials, data were cropped at points 0.5 seconds after and before the start and finish of the trials, respectively; this yielded a four second MVIC sample.[337] The mean MVIC amplitude was then used as a reference value for normalization of muscle activity.[200, 399] For the single-leg stop-jump trials, two samples were created: one for the 150msec interval before initial contact (muscle preactivity) and one for the 150msec interval after initial contact (muscle reactivity).[90, 91, 217] Integrated EMG (iEMG) was then calculated as the area under the curve for each sample.[24, 357, 391] The iEMG for both samples from each trial was then expressed as a percentage relative to the MVIC trial (%MVIC × sec).[217] Mean iEMG for the three single-leg stop-jump trials was used for data analysis. The Matlab R2012a program output the variables of interest was in text file format. All variables of interest were then extracted from the text file for statistical analyses.

3.7.2 Statistical Analysis

Statistical analyses was performed using STATA 12 (Statacorp LP, College Station, TX). Descriptive statistics were calculated for all variables. Separate multiple linear regression equations were fit for each of the dependent variables. Males were assigned a value ‘0’ and females were assigned a value ‘1’. Subject matter knowledge was incorporated in the model building process. All variables were examined individually. Summary statistics were computed and graphs plotted. Outliers were identified. Data transformations were performed where required. Pairwise scatter plots were created and examined for each variable. Correlation coefficients and collinearity diagnostics were calculated and performed and redundant variables were considered for deletion. The full model was fit and non-significant predictors were deleted. The reduced model was fit. Residuals were examined for linearity, heteroscedasticity, outliers, high leverage points, and influential points. Analysis was conducted to examine if additional variables could be dropped, and if new variables could be included in the model. If variables were dropped or added, then the model was fit and the steps outlined above were repeated (e.g.

non-significant predictors deleted, residuals re-examined). Information criteria were used to monitor the fitting process. For the final model, variance inflation factors and residual diagnostics were checked. If needed, the analysis was re-conducted to examine if additional variables could be dropped, and if new variables could be included in the model.[65] Statistical significance levels of 0.05 were established *a priori*.

4.0 RESULTS

The purpose of this study was to determine the extent to which gender and measures of knee mechanical joint stability, proprioception, and neuromuscular control predicted knee functional joint stability. Two multiple regression models were examined, each with a specific operational definition of knee functional joint stability as the outcome variable: 1. single-leg hop distance (cm) for the adapted crossover hop for distance test; 2. total knee valgus displacement (°) for the single-leg stop-jump test.

4.1 SUBJECTS

Thirty-six people expressed an interest in participating in this study. Two people did not fulfil the study eligibility criteria and were, therefore, excluded: one male had diabetes and one male did not meet the minimum physical activity requirements. Thirty-four subjects were enrolled: 18 males and 16 females representing 53% and 47% of the study sample, respectively. Demographic data for males, females, and the overall sample are presented in Table 2. Of all subjects, 15 males (44%) and eight females (23.5%) were agility-biased team sports athletes (American football, soccer, basketball, field hockey), and three males (9%) and eight females (23.5%) were CrossFit fitness enthusiasts. For the Noyes' Knee Sports Activity Rating Scale[278]

(Appendix A), subjects reported physical activities that ranged between 80 and 85 for Level II, or 95 and 100 for Level I. All subjects reported they were right-leg dominant.

Table 2. Demographic Summary Data

Demographic		**n**	**Mean**	**SD**	**Min**	**Med**	**Max**
Age (yrs)	Male	18	24.8	4.0	19.0	24.0	32.0
	Female	16	23.3	2.9	19.0	23.0	30.0
	All	34	24.1	3.5	19.0	23.0	32.0
Height (cm)	Male	18	177.9	7.1	167.0	178.3	194.0
	Female	16	165.0	7.2	153.0	165.0	177.0
	All	34	171.8	9.6	153.0	173.0	194.0
Mass (kg)	Male	18	78.5	8.9	63.7	79.7	91.4
	Female	16	61.7	8.8	48.9	61.1	81.8
	All	34	70.6	12.2	48.9	70.5	91.4
Sports Activity Rating Scale (0 - 100)	Male	18	89.4	7.8	80.0	90.0	100.0
	Female	16	92.5	6.6	80.0	95.0	100.0
	All	34	90.9	7.3	80.0	95.0	100.0

n = number of subjects; SD = standard deviation; Min = minimum; Med = median; Max = maximum
yrs = years; cm = centimeters; kg = kilograms

4.2 TOTAL KNEE VALGUS DISPLACEMENT OUTCOME VARIABLE: UNEXPECTED FINDINGS

The outcome variable for Hypothesis 2 was single-leg stop-jump total knee valgus displacement (TKVD; °) between initial contact and peak knee flexion. The outcome variable was calculated as: TKVD = peak knee valgus angle (°) – initial contact knee valgus angle (°). Total knee valgus displacement was, therefore, defined as the absolute difference between initial contact knee valgus angle and the furthest knee rotation in a valgus (abduction) direction up to the moment of peak knee flexion. The assumption underlying calculation of this variable was that the majority of the sample would demonstrate knee valgus displacement. This was not the case in this study. An unexpected finding was that the majority of subjects (n = 19; 56%) did not demonstrate any knee valgus displacement, but instead demonstrated knee varus displacement (knee rotation in a varus (adduction) direction). Of the 15 subjects (44%) who did demonstrate knee valgus displacement, eight (23.5%) were male and seven (20.5%) were female. Because the majority of subjects did not demonstrate any knee valgus displacement it was not possible to calculate an outcome variable (TKVD) for those subjects or perform the planned multiple regression analysis for Hypothesis 2. The decision was made, therefore, to conduct the analysis for Hypothesis 2 using the outcome variable valgus (−)/varus (+) displacement (°). The sign of the variable indicated directionality and was consistent with that used by the Vicon Nexus software.[378] Knee valgus displacement (−) was operationally defined as the absolute difference between initial contact knee valgus (−)/varus (+) angle and the furthest knee rotation in a valgus (abduction) direction up to the moment of peak knee flexion. Knee varus displacement (+) was operationally defined as the absolute difference between initial contact knee valgus (−)/varus (+) angle and the furthest knee rotation in a varus (adduction) direction up to the moment of peak knee flexion.

4.3 PREDICTOR AND OUTCOME VARIABLE SUMMARY DATA

Predictor and outcome variable summary data for males, females, and the overall sample are reported in Table 3. Males and females had similar mean, minimum, and maximum anterior tibial displacement. Males and females demonstrated similar mean knee active joint position sense absolute error, although females had higher minimum and maximum values compared to males. Females had higher mean medial hamstrings preactivity compared to males, whereas there were similar minimum, median, and maximum values between genders. Males and females demonstrated similar mean medial hamstrings reactivity, although males demonstrated higher maximum values compared to females. Males' mean hamstrings time-to-peak torque was approximately half that of females. Males had higher mean, minimum, median, and maximum adapted crossover hop for distance values compared to females, although females demonstrated lower variability (standard deviation, interquartile range) compared to males. Males and females demonstrated similar mean valgus/varus displacement, although females demonstrated lower minimum (−) and maximum (+) values reflecting more valgus displacement and less varus displacement compared to males. Mean and standard deviation valgus (−)/varus (+) angle for the entire sample normalized across single-leg stop-jump stance phase is illustrated in Figure 11.

Table 3. Predictor and Outcome Variable Summary Data

Predictor Variable		**n**	**Mean**	**SD**	**Min**	**Med**	**Max**	**25th %**	**75th %**
Anterior Tibial Displacement (mm)	Male	18	6.3	1.1	4.0	6.2	8.2	5.5	7.1
	Female	16	6.2	1.3	4.0	5.8	8.0	5.3	7.9
	All	34	6.3	1.2	4.0	6.0	8.2	5.5	7.4
Knee Active Joint Position Sense (°)	Male	18	3.5	2.1	0.8	3.0	8.8	1.8	5.0
	Female	16	3.6	2.7	1.4	2.7	12.3	1.8	4.8
	All	34	3.5	2.4	0.8	2.9	12.3	1.8	4.8
Medial Hamstrings Preactivity (%MVIC × sec)	Male	18	3.4	2.4	0.7	3.1	11.0	1.6	4.0
	Female	16	4.5	2.6	1.0	3.8	12.0	2.9	5.9
	All	34	3.9	2.5	0.7	3.4	12.0	2.3	5.2
Medial Hamstrings Reactivity (%MVIC × sec)	Male	18	10.2	5.1	4.5	9.0	24.6	6.7	13.6
	Female	16	11.0	3.4	5.8	10.0	16.6	8.8	14.4
	All	34	10.6	4.3	4.5	9.3	24.6	7.4	13.8
Hamstrings Time-to-Peak Torque (msec)	Male	18	166.7	79.6	90.0	120.0	280.0	100.0	262.5
	Female	16	231.9	75.6	110.0	280.0	310.0	142.5	280.0
	All	34	197.4	83.4	90.0	230.0	310.0	110.0	280.0
Outcome Variable		**n**	**Mean**	**SD**	**Min**	**Med**	**Max**	**25th %**	**75th %**
Adapted Crossover Hop for Distance (cm)	Male	18	711.6	111.2	472.7	749.2	864.7	633.1	791.5
	Female	16	501.7	68.2	338.7	507.8	616.7	457.5	539.8
	All	34	612.8	140.7	338.7	577.9	864.7	502.7	752.9
Valgus (−)/Varus (+) Displacement (°)	Male	18	6.0	7.3	-4.6	8.0	17.4	-1.1	12.8
	Female	16	5.7	7.0	-7.4	6.3	15.0	-0.2	12.4
	All	34	5.8	7.1	-7.4	7.5	17.4	-0.4	12.4

n = number of subjects; SD = standard deviation; Min = minimum; Med = median; Max = maximum
25th % = 25th percentile; 75th % = 75th percentile
mm = millimeters; MVIC = maximum voluntary isometric contraction; sec = seconds
msec = milliseconds; cm = centimeters

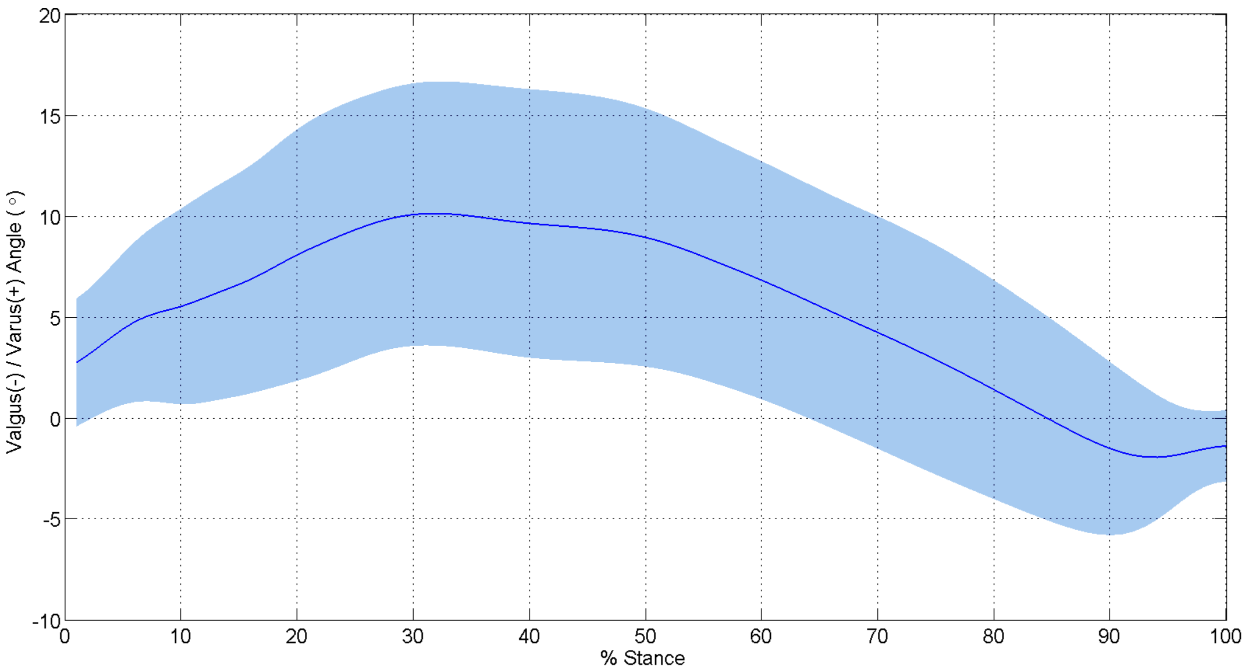

Figure 11. Mean and Standard Deviation Valgus/Varus Angle Normalized Across Single-Leg Stop-Jump Stance Phase

Solid line represents sample mean value, shaded area represents sample standard deviation (n=34)

4.4 NORMALITY OF DATA

Normality of data was assessed with the Shapiro-Wilk test. Of the outcome variables, the adapted crossover hop for distance demonstrated a normal distribution ($P > 0.05$), whereas valgus (−)/varus (+) displacement was found to have a non-normal distribution ($P = 0.01$). Of the predictor variables, medial hamstrings preactivity, medial hamstrings reactivity, and hamstrings time-to-peak torque were not normally distributed ($P \leq 0.01$). Transformations of subjects' valgus (−)/varus (+) outcome values were performed but were unsuccessful in normalizing the distribution of data. Further analyses were performed and are reported later.

4.5 BIVARIATE ANALYSES

Two-way scatterplot matrices for the predictor and outcome variables for Hypothesis 1 and Hypothesis 2 are illustrated in Figure 12 and Figure 13, respectively. Pearson correlation coefficient matrices for Hypothesis 1 and Hypothesis 2 are presented in Table 4 and Table 5, respectively.

For Hypothesis 1, visual inspection of the outcome variable and each predictor variable did not identify any outliers. (Figure 12). Most Pearson correlation coefficients were non-significant. Coefficients that were statistically significant were all less than 0.80, giving preliminary evidence there were no collinearity problems with data (Table 4). Further collinearity analyses were performed and are reported later.

For Hypothesis 2, visual inspection of the outcome variable and each predictor variable did not identify any outliers (Figure 13). Most Pearson correlation coefficients were non-significant. Coefficients that were statistically significant were all less than 0.80, giving preliminary evidence there were no collinearity problems with data (Table 5). Further collinearity analyses were performed and are reported later.

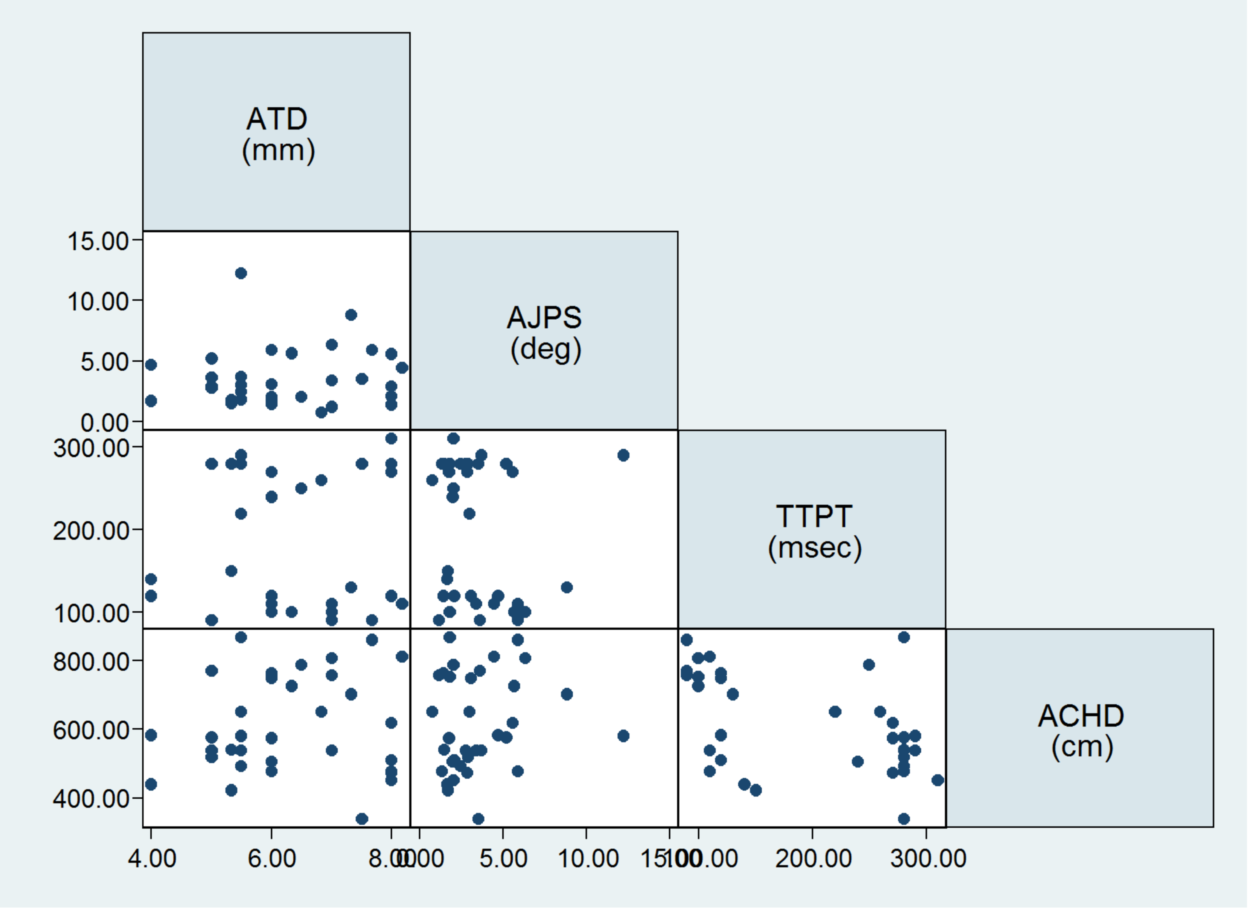

Figure 12. Two-Way Scatterplot Matrix for Hypothesis 1 Variables
Outcome Variable: Adapted Crossover Hop for Distance (cm)

ATD = anterior tibial displacement; AJPS = active joint position sense
TTPT = time-to-peak torque; ACHD = adapted crossover hop for distance

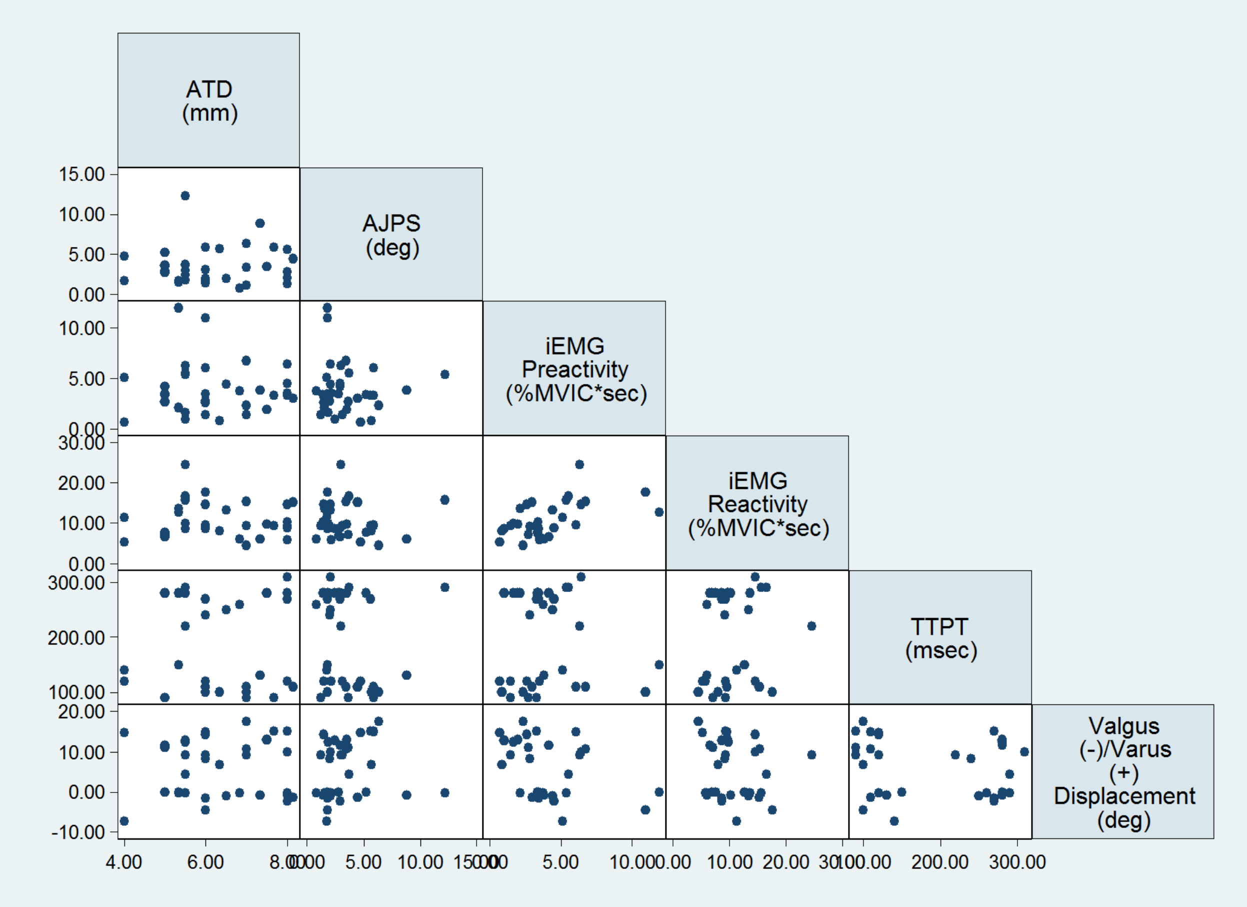

Figure 13. Two-Way Scatterplot Matrix for Hypothesis 2 Variables
Outcome Variable: Valgus (−)/Varus (+) Displacement (°)

ATD = anterior tibial displacement; AJPS = active joint position sense
iEMG = integrated electromyography; MVIC = maximum voluntary isometric contraction; sec = seconds
TTPT = time-to-peak torque

Table 4. Pearson's Correlation Coefficient Matrix for Hypothesis 1 Variables
Outcome Variable: Adapted Crossover Hop for Distance (cm)

	ATD	**AJPS**	**TTPT**	**ACHD**
ATD	1.00			
AJPS	0.05 (0.79)	1.00		
TTPT	-0.04 (0.82)	-0.12 (0.49)	1.00	
ACHD	0.09 (0.62)	0.15 (0.41)	**-0.46** **(0.01)**	1.00

ATD = anterior tibial displacement (mm)
AJPS = knee active joint position sense (°)
TTPT = hamstrings time-to-peak torque (msec)
ACHD = adapted crossover hop for distance (cm)
P value in parentheses

Table 5. Pearson's Correlation Coefficient Matrix for Hypothesis 2 Variables
Outcome Variable: Valgus (−)/Varus (+) Displacement (°)

	ATD	**AJPS**	**PREAC**	**REAC**	**TTPT**	**Val/Var**
ATD	1.00					
AJPS	0.05 (0.79)	1.00				
PREAC	-0.04 (0.84)	-0.06 (0.73)	1.00			
REAC	-0.03 (0.86)	-0.08 (0.66)	**0.53** **(0.00)**	1.00		
TTPT	-0.04 (0.82)	-0.12 (0.49)	-0.04 (0.82)	0.09 (0.60)	1.00	
Val/Var	0.04 (0.83)	0.14 (0.42)	**-0.37** **(0.03)**	-0.16 (0.38)	-0.18 (0.31)	1.00

ATD = anterior tibial displacement (mm)
AJPS = knee active joint position sense (°)
PREAC = medial hamstrings preactivity (%MVIC × sec)
REAC = medial hamstrings reactivity (%MVIC × sec)
TTPT = hamstrings time-to-peak torque (msec)
Val/Var = valgus (−)/varus (+) displacement (°)
P value in parentheses

4.6 SIMPLE LINEAR REGRESSION ANALYSES

Findings for simple linear regression analyses for Hypothesis 1 are presented in Table 6. Significant regressions were found for gender and the adapted crossover hop for distance, and for hamstrings time-to-peak torque and the adapted crossover hop for distance. For the gender equation, 57% of the variance in the adapted crossover hop for distance was explained by being male or female. Males hopped further than females. For the hamstrings time-to-peak torque equation, 21% of the variance in the adapted crossover hop for distance was explained by the time-to-peak torque. For every unit increase in time-to-peak torque, hop distance decreased 0.78cm. The reciprocal of this was that as time-to-peak torque decreased, hop distance increased. The overall *F*-test was significant. The signs of the significant predictor variables' coefficients were reasonable and consistent with expert knowledge and expectation.

Findings for simple linear regression analyses for Hypothesis 2 are presented in Table 7. A significant regression was found for medial hamstrings preactivity and valgus (−)/varus (+) displacement. For this equation, 14% of the variance in single-leg stop-jump valgus/varus displacement was explained by medial hamstrings preactivity. For every unit increase in medial hamstrings preactivity, valgus/varus displacement decreased 1.03°. The overall *F*-test was significant. Because the valgus direction was designated by a negative sign, this regression indicated that increased medial hamstrings preactivity was associated with knee displacement that progressed in a valgus direction. This finding was unexpected and, therefore, all data points for medial hamstrings preactivity were reviewed prior to further analyses and found to be legitimate.

Table 6. Summary Table for Simple Linear Regression Models for Hypothesis 1 Outcome Variable: Adapted Crossover Hop for Distance (cm)

Predictor Variable	**n**	**Coefficient**	**Model MSE**	R^2	**Model *P* Value**
Gender (Male 0; Female 1)	34	-209.91	373231.83	**0.57**	**0.00**
Anterior Tibial Displacement (mm)	34	10.28	4969.14	0.01	0.62
Knee Active Joint Position Sense (°)	34	8.61	14094.38	0.02	0.41
Hamstrings Time-to-Peak Torque (msec)	34	-0.78	139004.01	**0.21**	**0.01**

cm = centimeters; n = number of subjects; MSE = mean square error term; mm = millimeters; msec = milliseconds

Table 7. Summary Table for Simple Linear Regression Models for Hypothesis 2 Outcome Variable: Single-Leg Stop-Jump Valgus (−)/Varus (+) Displacement (°)

Predictor Variable	**n**	**Coefficient**	**Model MSE**	R^2	**Model *P* Value**
Gender (Male 0; Female 1)	34	-0.26	0.59	0.00	0.91
Anterior Tibial Displacement (mm)	34	0.23	2.54	0.00	0.83
Knee Active Joint Position Sense (°)	34	0.42	34.23	0.02	0.42
Medial Hamstrings Preactivity (%MVIC × sec)	34	-1.03	223.39	**0.14**	**0.03**
Medial Hamstrings Reactivity (%MVIC × sec)	34	-0.26	40.82	0.02	0.38
Hamstrings Time-to-Peak Torque (msec)	34	-0.02	52.29	0.03	0.31

n = number of subjects; MSE = mean square error term; mm = millimeters
MVIC = maximum voluntary isometric contraction; sec = seconds; msec = milliseconds

4.7 SIMPLE LINEAR REGRESSION ANALYSES DIAGNOSTICS

The assumptions underlying linear regression analysis for the outcome and predictor variables for both hypotheses were assessed by examining for linearity, homoscedasticity, and outliers. For Hypothesis 1, visual inspection of two-way scatterplots for predicted (fitted) values vs. jackknife (studentized) residuals revealed no obvious evidence of lack of linearity, lack of homoscedasticity, or presence of outliers (studentized residuals within −3.0 to +3.0) (Figure14). Homogeneity of variance of all models was confirmed by non-significant ($P > 0.05$) Breusch-Pagan tests for heteroscedasticity.

For Hypothesis 2, visual inspection of two-way scatterplots for predicted (fitted) values vs. jackknife (studentized) residuals revealed no obvious evidence of lack of linearity, lack of homoscedasticity, or presence of outliers (studentized residuals within −3.0 to +3.0) (Figure15). Homogeneity of variance of all models was confirmed by non-significant ($P > 0.05$) Breusch-Pagan tests for heteroscedasticity.

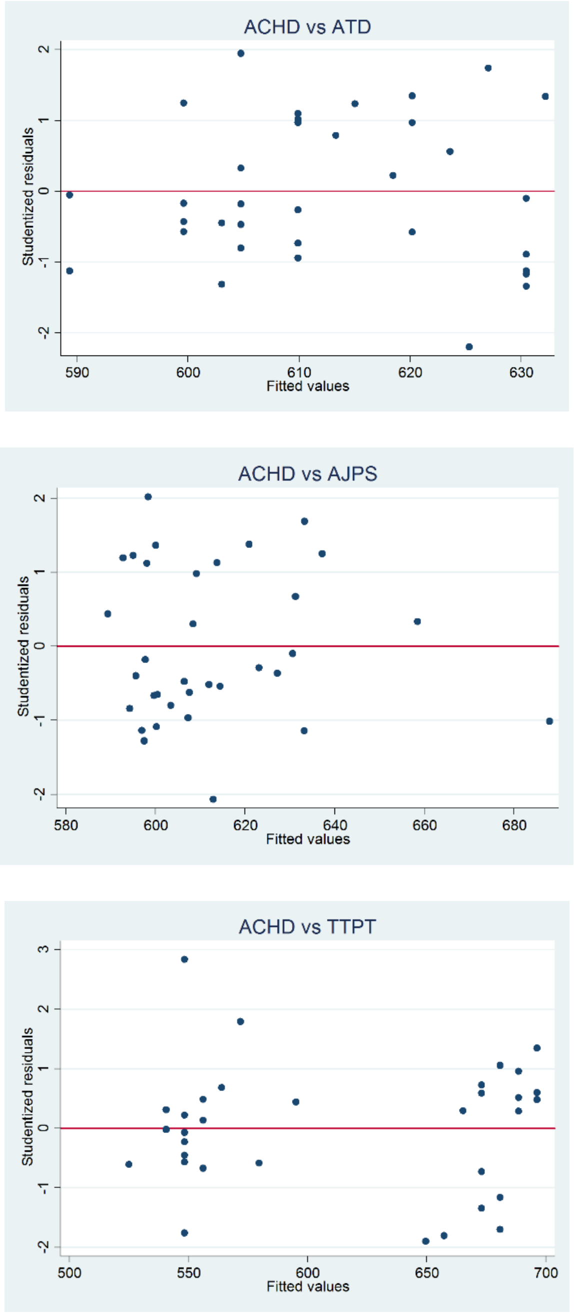

Figure 14. Simple Linear Regression Fitted Value vs. Jackknife Residual Plots for Hypothesis 1 Outcome Variable: Adapted Crossover Hop for Distance (cm)

ACHD = adapted crossover hop for distance; ATD = anterior tibial displacement
AJPS = active joint position sense; TTPT = time-to-peak torque

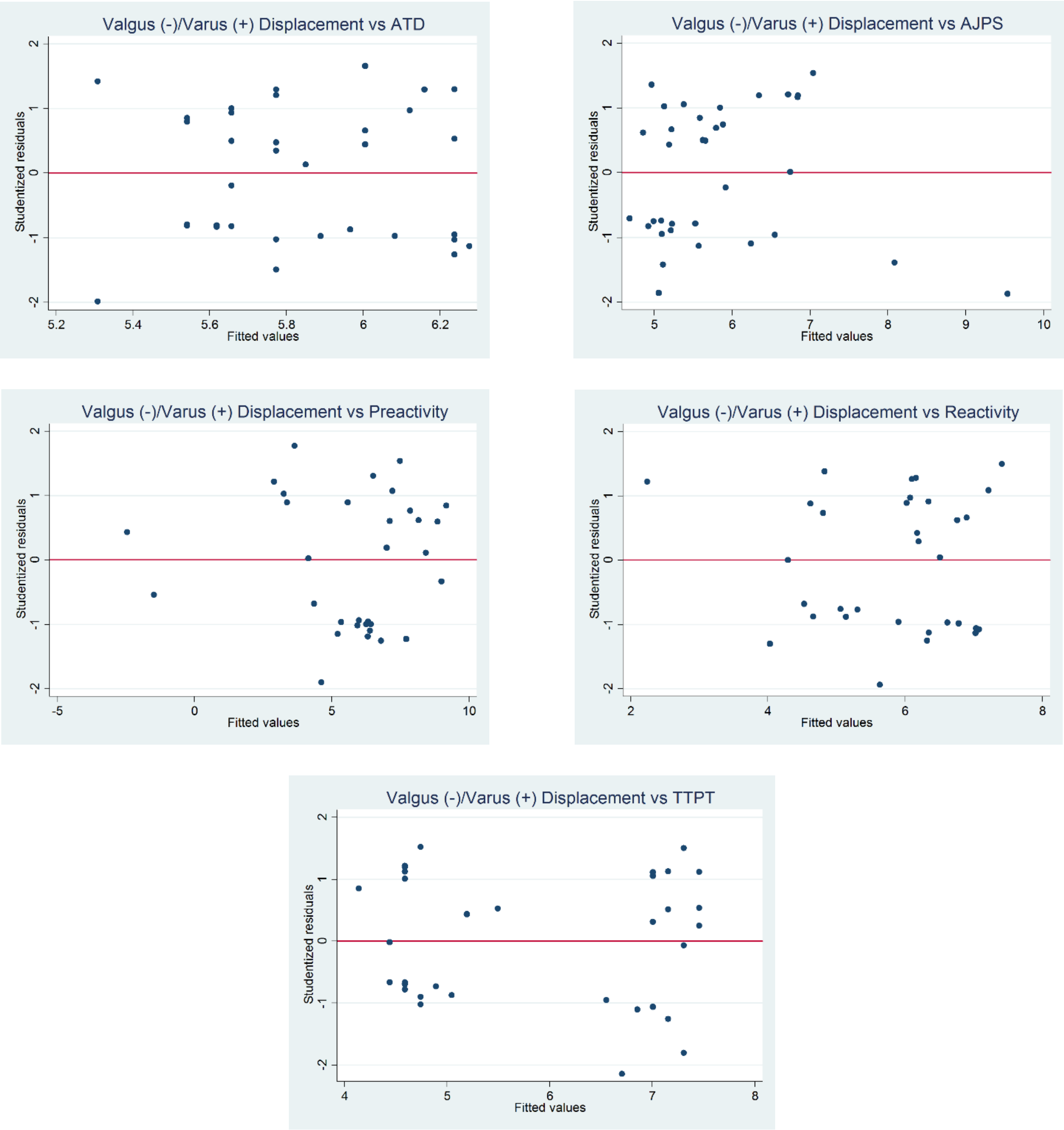

Figure 15. Simple Linear Regression Fitted Value vs. Jackknife Residual Plots for Hypothesis 2 Outcome Variable: Valgus (−)/Varus (+) Displacement (°)

ATD = anterior tibial displacement; AJPS = active joint position sense; TTPT = time-to-peak torque

4.8 MULTIPLE LINEAR REGRESSION ANALYSES

Backward stepwise regression analyses were performed for both hypotheses. For Hypothesis 1, anterior tibial displacement and active joint position sense were both removed from the model during the backward stepwise procedure as non-significant predictors of adapted crossover hop for distance single-leg hop distance. The multiple linear regression model including gender ($\beta = -188.79$, $P = 0.00$) and hamstrings time-to-peak torque ($\beta = -0.32$, $P = 0.13$) as predictor variables resulted in a significant model that accounted for 60% of the overall variance in adapted crossover hop for distance single-leg hop distance ($R^2 = 0.60$, $P = 0.00$). Regression diagnostics including a two-way scatterplot of the fitted values vs. the Jackknife residuals suggested a cluster effect (bimodal distribution) (Figure 16). A Shapiro-Wilk test assessing for normality of residuals was non-significant ($P = 0.86$) indicating data were normally distributed. The Variance Inflation Factor (VIF) for predictor variables was 1.19 indicating an absence of collinearity problems. Analysis for outliers in the outcome variable was performed by examining the distribution of jackknife (studentized) residuals:[65] critical values were calculated using the STATA "invttail(*df*,*P*)" function. This procedure did not indicate the presence of outliers. Visual inspection of a two-way scatterplot for predicted (fitted) values vs. jackknife (studentized) residuals also did not indicate the presence of outliers (Figure 16). Analysis for high leverage in the predictor variables was performed using Hadi's Influence (H_i).[65] This procedure did not reveal any problematic data points. Visual inspection of a boxplot of potential high leverage values confirmed the absence of extreme values (Figure 17). Further analysis using Cook's Distance (Cook's D_i) and a cut-off $D_i > 1.00$[65] did not indicate the presence of influential points. The final multiple linear regression was fit with gender ($\beta = -188.79$) and time-to-peak torque ($\beta = -0.32$) being included in the final model. Because males were the reference group designated with the value zero and females were designated with the value one, the negative sign of the beta coefficient indicates that males hopped further than females. The final model is summarized in Table 8.

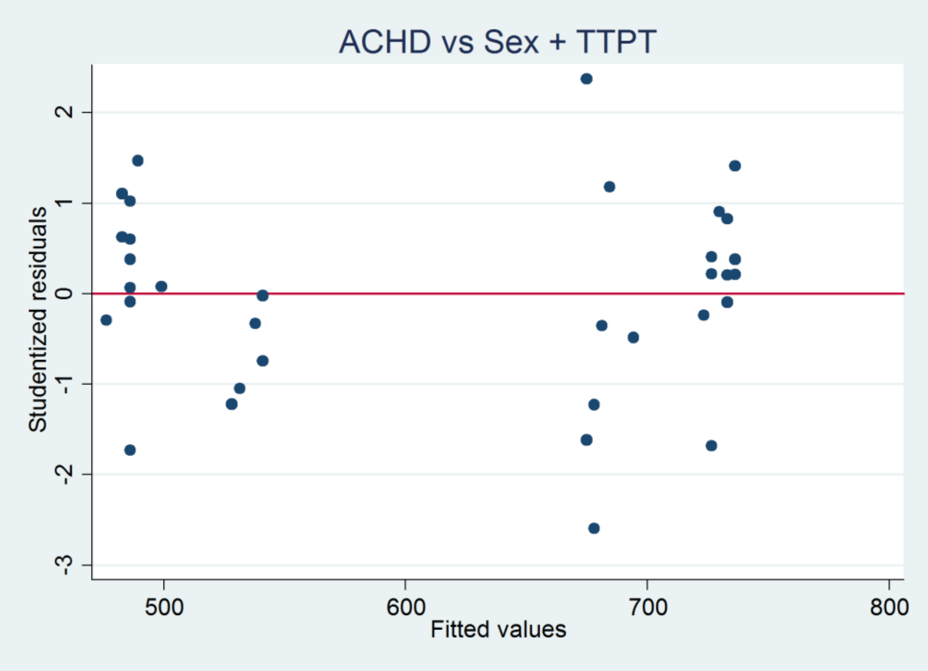

Figure 16. Two-Way Scatterplot of Fitted Value vs. Jackknife Residual for Hypothesis 1 Adapted Crossover Hop for Distance vs. Gender + Time-to-Peak Torque

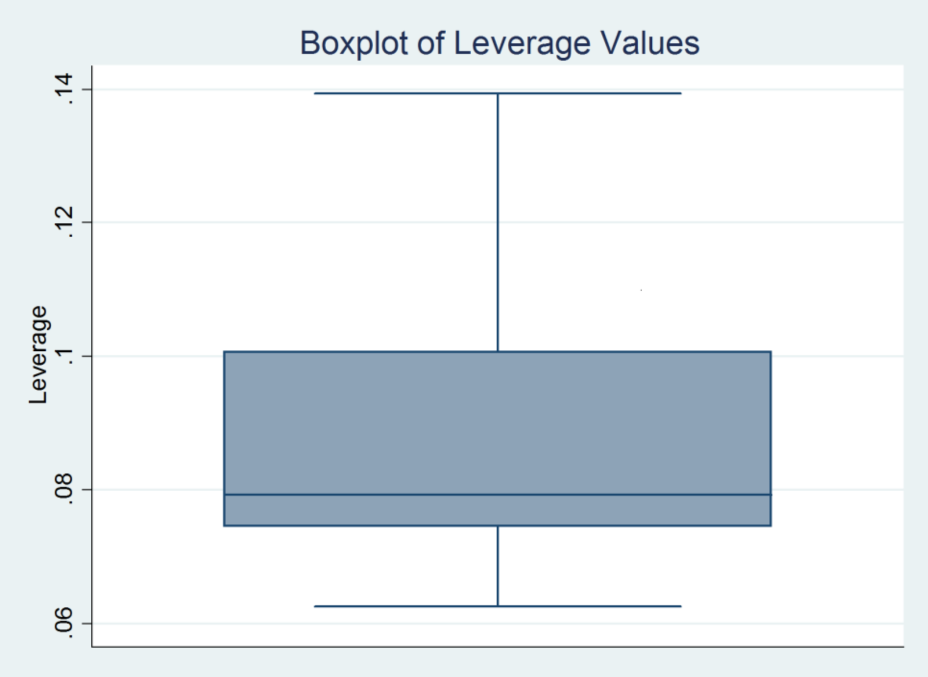

Figure 17. Boxplot of Leverage Values for Hypothesis 1
Adapted Crossover Hop for Distance vs. Gender + Time-to-Peak Torque

Table 8. Summary Table for Final Model for Hypothesis 1
Outcome Variable: Adapted Crossover Hop for Distance (cm)

	Coefficient	**Standard Error**	***P* Value**
Constant	765.52	40.87	0.00
Gender (Male 0; Female 1)	−188.79	34.26	0.00
Time-to-Peak Torque (msec)	−0.32	0.21	0.13

$F\ (2, 31) = 23.47, P = 0.00$

$R^2 = 0.60$

msec = milliseconds

For Hypothesis 2, gender, anterior tibial displacement, active joint position sense, medial hamstrings reactivity, and hamstrings time-to-peak torque were removed from the model during the backward stepwise procedure as non-significant predictors of valgus (−)/varus (+) displacement. The multiple linear regression including medial hamstrings preactivity ($\beta = -1.03$, $P = 0.03$) as the sole predictor variable resulted in a significant model that accounted for 14% of the overall variance in adapted crossover hop for distance single-leg hop distance ($R^2 = 0.14$, $P = 0.03$). Regression diagnostics including a two-way scatterplot of the fitted values vs. the Jackknife residuals (Figure 18) suggested potential outliers. A Shapiro-Wilk test assessing for normality of residuals was significant ($P = 0.03$) indicating a non-normal distribution of residuals. The Variance Inflation Factor (VIF) for predictor variables was 1.00. Analysis for outliers in the outcome variable did not indicate the presence of problematic observations. Analysis for high leverage in the predictor variables using H_i suggested problematic data points. This was confirmed by the presence of extreme values on visual inspection of a boxplot of potential high leverage values. (Figure 19). Further analysis using Cook's D_i did not, however, suggest the presence of influential points. Robust regression using medial hamstrings preactivity as the sole predictor variable resulted in a significant ($P = 0.00$) contribution to the final model. The final multiple linear regression was fit with medial hamstrings preactivity ($\beta = -1.03$) remaining as the only predictor variable that accounted for 14% of the total variance in valgus (−)/varus (+) displacement ($R^2 = 0.14$, P = 0.03). Because the valgus direction was designated by a negative sign, and the beta coefficient was of a negative sign, this robust regression indicated that increased medial hamstrings preactivity was associated with knee displacement that progressed in a valgus direction. The final model is summarized in Table 9. However, diagnostics had indicated that residuals were not normally distributed. Transformations were, therefore, performed on the outcome variable in an attempt to achieve normal distribution of residuals:[65, 298] square root and log transformations were executed using the STATA "ladder *variable name*" function; reciprocal transformation was executed using $X' = 1/X+1$.[298] All transformations were unsuccessful as evidenced by significant (*P* = 0.00) Shapiro-Wilk tests. Further transformations were attempted. Prior to further transformations, valgus (−)/varus (+) values were made more positive by adding eight to every subject's mean value. A value of eight was chosen because the largest valgus value was −7.4° (Table 3). Thus, all subjects' values were then positive values. The square root, log, and reciprocal transformations were repeated. Again, all transformations were unsuccessful as evidenced by significant (*P* = 0.00) Shapiro-Wilk tests. Because the transformation procedures employed here were unsuccessful at normalizing the distribution of residuals, it was clear that linear regression was not the appropriate statistical method for analyzing this data.

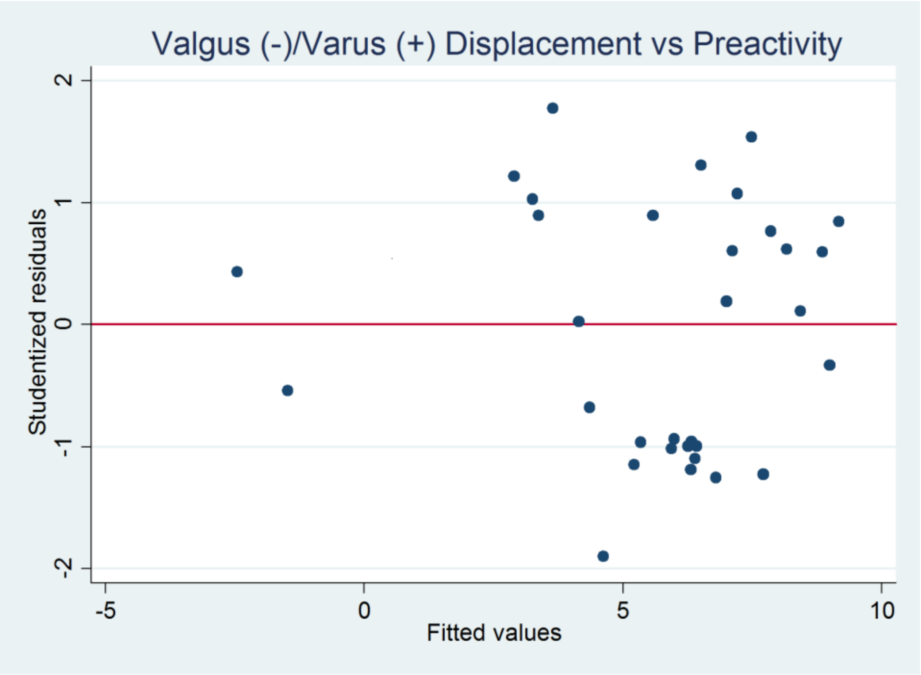

Figure 18. Two-Way Scatterplot of Fitted Value vs. Jackknife Residual for Hypothesis 2
Valgus (−)/Varus (+) Displacement vs. Medial Hamstrings Preactivity

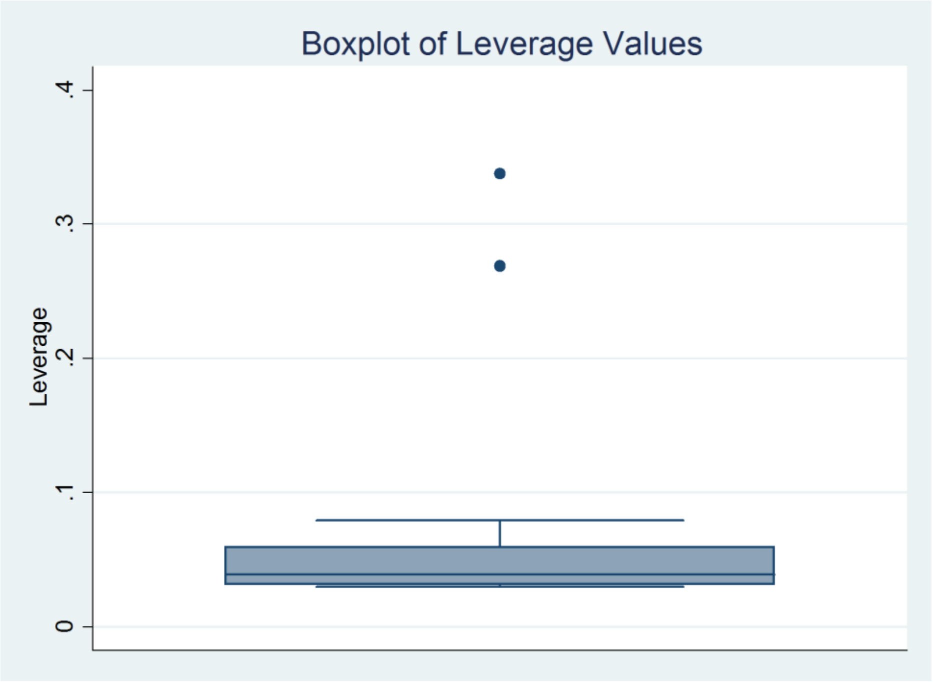

Figure 19. Boxplot of Leverage Values for Hypothesis 2
Valgus (−)/Varus (+) Displacement vs. Medial Hamstrings Preactivity

Table 9. Summary Table for Model for Hypothesis 2
Outcome Variable: Valgus (−)/Varus (+) Displacement (°)

	Coefficient	**Standard Error**	**P Value**
Constant	9.89	1.64	0.00
Medial Hamstrings Preactivity (%MVIC × sec)	−1.03	0.31	0.00

F (1, 32) = 10.76, P = 0.00

$R^2 = 0.14$

MVIC = maximum voluntary isometric contraction; sec = seconds

5.0 DISCUSSION

The purpose of this study was to determine the extent to which gender and measures of knee mechanical joint stability, proprioception, and neuromuscular control predicted knee functional joint stability. Physically active males and females participated in one test session that included measurements performed on the dominant limb: prone knee extension (hamstring-biased eccentric-to-isometric) active joint position sense, anterior tibial displacement, adapted crossover hop for distance single-leg hop distance, single-leg stop-jump surface electromyography (medial hamstrings preactivity and reactivity) and kinematics (stance phase knee valgus/varus), and isokinetic knee flexion (hamstrings) time-to-peak torque. Two multiple regression models were planned, each with a specific operational definition of knee functional joint stability as the outcome variable: 1. single-leg hop distance (cm) for the adapted crossover hop for distance test; 2. total knee valgus displacement (°) for the single-leg stop-jump test. An unexpected finding was that the majority of the sample recruited for this study did not demonstrate any knee valgus displacement during the single-leg stop-jump test. The second regression analysis was, therefore, performed using the outcome variable valgus (−)/varus (+) displacement (°). The two hypotheses were:

Hypothesis 1: Gender, anterior tibial displacement, prone knee extension active joint position sense absolute error, and knee flexion time-to-peak torque would significantly predict adapted crossover hop for distance single-leg hop distance. As anterior tibial displacement, prone knee extension active joint position sense absolute error, and knee flexion time-to-peak torque all decrease then adapted crossover hop for distance single-leg hop distance would increase. Also, males will hop further than females.

Hypothesis 2: Gender, anterior tibial displacement, prone knee extension active joint position sense absolute error, medial hamstrings preparatory muscle activity, medial hamstrings reactive muscle activity, and knee flexion time-to-peak torque would significantly predict single-leg stop-jump knee valgus/varus displacement. As anterior tibial displacement, prone knee extension active joint position sense absolute error, and knee flexion time-to-peak torque all decrease, and medial hamstrings preparatory and reactive muscle activity both increase, then knee valgus displacement would decrease. Also, males would have less knee valgus displacement than females.

For Hypothesis 1, only gender and knee flexion (hamstrings) time-to-peak torque contributed to a final model that predicted 60% of the variance in the adapted crossover hop for distance single-leg hop distance. These results only partially support Hypothesis 1 since two of the original four predictor variables were retained in the final equation. For Hypothesis 2, medial hamstrings preactivity was the only significant predictor that contributed to a final model that predicted 14% of the variance in single-leg stop-jump knee valgus/varus displacement. However, normality screening of raw valgus/varus data and normality diagnostics for valgus/varus regression residuals revealed that data had a non-normal distribution. Regression analysis was not, therefore, the appropriate statistical method for analyzing this data. Subject characteristics, outcome variables, predictor variables, study hypotheses and findings, study limitations, study significance, and future research directions will now be discussed in more detail in the following sections.

5.1 SUBJECT CHARACTERISTICS

Subjects were included in this study if they were physically active males/females. The term "physically active" was defined as participating in Level II sports or higher according to the Noyes' Knee Sports Activity Rating Scale,[278] which includes physical activities and movement patterns (running, twisting, turning, jumping, pivoting, cutting) that are also typical components of exercise programs commonly performed by fitness enthusiasts (e.g. circuit training, CrossFit).[386, 387] Therefore, in addition to sports athletes, fitness enthusiasts engaged in training programs that include running/twisting/turning/pivoting/cutting were also candidates for this study. Based on the information provided by subjects, all were indeed regular participants in agility-biased physical activities that demanded deceleration maneuvers such as landing from a jump or cutting to suddenly change direction when running. Thus, the current subject sample displays the physical activity characteristics intended by this study's recruitment methods and inclusion criteria.

5.2 OUTCOME VARIABLES

5.2.1 Adapted Crossover Hop for Distance Single-Leg Hop Distance

Single-leg hop tests have excellent clinical utility as indirect measures of knee functional joint stability (dynamic stability),[70, 115] and their routine use is recommended in all aspects of knee injury control decision-making.[104, 232, 233] The adapted crossover hop for distance[73] was used in this study as a clinical and indirect measure of knee functional joint stability. The current group mean value is consistent with that of previous work employing a mixed group of uninjured male and female agility-biased team sports athletes (601.6 ± 117.6cm),[73] and similar to the uninjured limb of a mixed group of male and female recreational athletes approximately 12 months after ACL-R (566.6 ± 146.1cm).[72] Considering the genders separately, the males did not hop as far as other males regularly participating in agility-biased sports (808.1 ± 88.2cm),[71] whereas the females hopped further than a group of elite female basketball players (≈ 350cm).[156] In comparison with previous research, the values obtained for the adapted crossover hop for distance test in this study are supported as valid data points.

5.2.2 Single-Leg Stop-Jump Knee Valgus/Varus Displacement

Measurement of knee valgus/varus kinematics during single-leg functional tasks has been used as a laboratory-based direct measure of knee functional joint stability (alignment).[2, 31, 53, 290, 337] The single-leg stop jump was employed in this study because it is a high-demand task that simulates sudden deceleration movement patterns specific to agility-biased team sports and elicits knee valgus kinematics in male and female athletes.[2, 31, 337] It was observed, however, that 56% of subjects did not demonstrate knee valgus displacement during the single-leg stop-jump task. Further, normality screening of raw valgus/varus data revealed that data had a non-normal distribution. These were unexpected findings and so an explanation was sought. All subject trials and data processing procedures were meticulously reviewed in their entirety. There appeared to be no errors in kinematic data collection, data processing, or data transfer procedures. Single-leg stance can result in a center-of-mass that is located medial to the stance leg.[62, 192] The line-of-gravity from the center-of-mass is directed downwards and medial to the knee joint creating a knee varus (adduction) moment.[62, 192] The knee varus moment can tend to “thrust” the knee into a more varus versus valgus alignment during single-leg stance,[13] which may explain why other work has also reported that single-leg landings result in knee alignment that is towards a more neutral or varus alignment versus a more valgus alignment.[118, 157, 323] The findings of this study are, therefore, comparable to the pattern of knee kinematics observed in the stance phase of other single-leg functional tasks. In light of this, and combined with the absence of any kinematic data collection or processing errors, all current data points were accepted and supported as being representative of knee valgus/varus kinematics within the context of the single-leg stop-jump testing procedure used in this study.

5.3 PREDICTOR VARIABLES

5.3.1 Gender

The mechanism of noncontact knee injury involves a combined movement pattern of knee flexion, knee valgus, ATD, and tibial internal rotation that is commonly experienced by both male and female agility-biased team sports athletes.[203, 204, 208] Females can demonstrate statistically significant differences in mechanical joint stability and sensorimotor control characteristics when compared to males.[63, 174, 218, 320, 341] This study recruited both male and female subjects and gender was employed as a variable in statistical analyses. Males and females were recruited for this study with almost equal proportions. The external validity (generalizability) of this study relative to the characteristics of the sample is, therefore, strengthened by the almost equal proportion of male and female subjects.

5.3.2 Knee Active Joint Position Sense

Proprioception is critical for mediating appropriate feedforward and feedback neuromuscular control of functional joint stability.[249, 308, 319] The prone knee extension active joint position sense (AJPS) test was used in this study to bias the hamstrings muscle group. An eccentric-to-isometric sequence of testing was performed to focus mechanical stimuli on the muscle spindle. This is the first study to report use of a prone hamstrings-biased eccentric-to-isometric AJPS test for measuring knee proprioception at a 45° target angle from which the absolute error variable was extracted. It is not possible, therefore, to directly compare the data from this study with any other published work. It is possible, alternatively, to indirectly compare the data from this study to other research that has used other types of knee AJPS test to elicit absolute error variables at similar angles of knee flexion. Mean absolute error values observed in this study were almost identical between males and females. Overall group mean values are lower than data reported for uninjured subjects performing AJPS tests involving prone knee flexion (concentric-to-isometric hamstrings; target angle = 45° knee flexion; mean ± SD = 4.1 ± 2.5°),[136] seated knee extension (concentric-to-isometric quadriceps; target angle = 45° knee flexion; median = 4.7°),[57] and seated knee flexion (eccentric-to-isometric quadriceps; target angle = 30° knee flexion; mean ± SD = 6.1 ± 3.2°).[99] Because the present study's mean absolute error values are lower than values reported for other knee AJPS tests, and because there were no apparent errors in kinematic data collection or data processing procedures, all data points were supported as being an accurate representation of hamstrings-biased AJPS within the context of the current test procedure.

5.3.3 Anterior Tibial Displacement

Mechanical joint stability contributes to optimal functional joint stability[43, 185, 280, 363] and a valid clinical impression regarding an individual's knee functional joint stability cannot be formed unless the status of the individual's knee mechanical joint stability is also known. The KT-1000 was used in this study to directly quantify anterior tibial displacement (ATD) as a measure of knee mechanical joint stability and a component of knee functional joint stability. The manual maximum test was used as recommended in previous work.[80, 81] The current ATD mean values are comparable to the mean values reported for experienced male (5.8mm) and female (5.0mm) testers measuring uninjured knees,[17] and lies within the range of ATD reference values for uninjured knees (5.0 − 15.0mm) observed by other authors.[81, 303] In comparison with previous published research, the values obtained for ATD in this study are supported as valid data points.

5.3.4 Medial Hamstrings Preactivity and Reactivity

Feedforward and feedback muscle activation is important for increasing preparatory and reactive muscle stiffness and enhancing knee functional joint stability.[175, 225, 363] This study collected muscle activation data during the single-leg stop-jump task using sEMG. Feedforward activation was sampled for the 150msec timeframe prior to initial contact (preactivity), and feedback muscle activation was sampled for the 150msec timeframe after initial contact (reactivity).[217] Both preactivity and reactivity were quantified using the iEMG variable %MVIC × sec.[217] No other published work has employed iEMG to quantify medial hamstrings preactivity or reactivity during the single-leg stop-jump task using the same events or timeframes specified in this study. It is not possible then to directly compare the mean preactivity or reactivity values from this study with any other work. It is possible, however, to indirectly compare the pattern of change (increase/decrease) between preactivity and reactivity seen in this study with other research that has employed sEMG and iEMG during athletic tasks. Lephart et al.[217] measured medial hamstrings mean preactivity and reactivity during a vertical jump-landing task in two groups of athletes undertaking different types of training program. Data were sampled in a pre-/post- study design before and after eight weeks of training. For both groups prior to the intervention period, mean iEMG (%MVIC × sec) increased from before to after initial contact: medial hamstrings mean reactivity was higher than mean preactivity. Therefore, with regard to the pattern of change in iEMG during an athletic task, the findings of this study are consistent with other work. Meticulous and thorough data collection quality control procedures were in place during this study. There appeared to be no errors in data collection or data processing procedures and so all data points were supported as being representative of medial hamstrings preactivity and reactivity within the context of the single-leg stop-jump testing procedure used in this study.

5.3.5 Isokinetic Hamstrings Time-to-Peak Torque

The timely generation of muscle force as a result of feedback neuromuscular control is important to reduce excessive knee joint displacements and correct knee joint alignment in potential injury situations,[176, 394, 395] and knee muscle time-to-peak torque (TTPT) is, therefore, an important variable for consideration in noncontact knee injury control programs.[146] This study sampled dynamic hamstrings TTPT using an isokinetic dynamometer at $240°\cdot sec^{-1}$ in a 0-60° knee flexion ROM. To date, no other research has been published that includes the collection of hamstring TTPT data using the exact same test parameters (e.g. 0-60° knee flexion ROM). It is not possible, consequently, to directly compare the results of this study to other works. However, it is possible to compare the present data to research published by other authors using the same isokinetic testing velocity. The current male mean hamstrings TTPT data is comparable to that reported for other athletic male subjects (ROM = not specified; TTPT = 150msec), but the current female TTPT values are greater than those reported for other athletic female subjects (ROM = not specified; TTPT = 169msec).[174] The current group mean hamstrings TTPT data is comparable to the mean data for another group of physically active subjects (ROM = 30-60° knee flexion; TTPT = 197.1 ± 72.6msec).[44] Following isokinetic data collection in this study, a text file generated by the dynamometer software was reviewed to verify every subject achieved a test velocity of 240 ± $5°\cdot sec^{-1}$ and a ROM of 60 ± 5° to 0 ± 5°. Because each subject's text file confirmed an acceptable test velocity and ROM was achieved, all data points were supported as being an accurate representation of hamstrings TTPT within the context of the current test procedure

5.4 STUDY HYPOTHESES AND FINDINGS

5.4.1 Hypothesis 1: Predictors of the Adapted Crossover Hop for Distance Single-Leg Hop Distance

Gender, prone knee extension AJPS, ATD, and knee hamstrings TTPT were examined as potential predictors of the adapted crossover hop for distance single-leg hop distance. Single-leg hop tests are indirect measures of knee functional joint stability and hop distance is an important variable because multi-directional single-leg hop tests are clinically capable of predicting those who will regain knee functional joint stability defined by patient self-report of return-to-function after knee ligament injury and/or surgical reconstruction.[103, 147, 170, 231] American and European best practice guidelines recommend, therefore, that single-leg multi-directional hop tests are routinely employed as part of a test battery intended to fully characterize knee functional joint stability.[104, 232, 233, 258] Only gender and hamstrings TTPT contributed to a final model that significantly predicted 60% of the variance in the adapted crossover hop for distance single-leg hop distance. These results only partially support Hypothesis 1 since two of the original four predictor variables were retained in the final equation. The equation indicated that males would hop further than females, and that as TTPT decreased hop distance would increase.

Males consistently demonstrate more favorable knee mechanical joint stability,[174, 320] proprioception,[320] neuromuscular control,[218, 320, 341] and biomechanical characteristics[64, 218, 341] than females. The finding that males are consistently stronger than females[174, 218] likely explains why males typically demonstrate better outcomes (greater distances) in single-leg hop tests.[256] Thus, it is not surprising that gender was a significant predictor of hop distance in this study. Males hopped further than females. This finding is in partial support of Hypothesis 1. The clinical significance of this finding is that if the adapted crossover hop for distance is to be used as a clinical and indirect measure of knee functional joint stability, a female athlete's performance of the test should not be interpreted solely in comparison to that of a male athlete's performance. A female athlete's performance of single-leg hop tests should also be carefully interpreted in line with what is known about female-specific mechanical joint stability, proprioception, neuromuscular control, and biomechanical characteristics. Only then can informed decisions be made regarding the specific content of knee injury prevention and rehabilitation programs for both genders when the outcome of such programs is partly determined by single-leg hop test performance.

Proprioception is critical for mediating appropriate feedforward and feedback neuromuscular control of functional joint stability.[249, 308, 319] In this study, prone knee extension AJPS as a measure of hamstrings-biased eccentric-to-isometric proprioception was not retained in the final model. The AJPS component of Hypothesis 1 was not supported. This finding is consistent with previous work that has been unable to demonstrate strong associations between different tests of knee proprioception and single-leg hop tests as indirect measures of knee functional joint stability in uninjured and injured subjects.[42, 99, 125, 194, 312] The mean AJPS values observed in this study are smaller than the mean values reported for other knee AJPS tests.[57, 99, 136] The mean AJPS test values observed in this study are not, however, smaller than the mean threshold-to-detection of passive motion (TTDPM) values observed by other authors studying sensorimotor control of the knee.[42, 273, 320] Single-leg hop tests are reliable, valid, and useful clinical measures of knee functional joint stability.[70, 73, 115, 232, 233] Proprioception is critical for mediating neuromuscular control of knee functional joint stability.[43, 308, 363] Explanation then as to why the prone knee extension test was not retained as a predictor of hop distance is that the test may not have been sensitive enough to detect clinically important differences between subjects. The size of clinically important proprioceptive differences between limbs or subjects remains unknown.[138] Sub-optimal proprioceptive function that is relevant to the onset of first-time knee injury, onset of re-injury, as well as osteoarthrosis progression may not be detectable by current proprioception testing methods.[317] Previous work in our laboratory has reported reference data for knee proprioceptive acuity defined by TTDPM moving into extension.[273, 320] The mean values reported by our laboratory's past TTDPM work were lower than the mean value measured using the present AJPS test.[273, 320] This suggests TTDPM testing methods may actually be more sensitive to clinically important proprioceptive differences between limbs or subjects than AJPS testing methods. Taken together then, the results of this study and previous AJPS and TTDPM work suggest that more research needs to be performed on identifying different and potentially more sensitive tests of knee proprioception. The clinical significance of the present finding is that hamstring-biased eccentric-to-isometric proprioception may not be an important component of noncontact knee injury prevention and rehabilitation programs where knee functional joint stability is defined by multi-directional single-leg hop tests.

Mechanical joint stability contributes to optimal functional joint stability.[185, 280, 308] A valid clinical impression regarding an individual's knee functional joint stability cannot be formed unless the status of the individual's knee mechanical joint stability is also known. In the current work, ATD as a measure of knee mechanical joint stability was not retained in the final prediction model. The ATD component of Hypothesis 1 was not supported. This finding is in agreement with earlier research that also did not identify a strong association between ATD and knee functional joint stability defined by single-leg hop tests[103, 105, 170, 312, 336, 344] or ATD and knee functional joint stability defined by agility-biased running tests.[221] There is evidence that knee functional joint stability can be maintained despite isolated knee ligament (mechanical) deficiency as demonstrated by previously injured athletes' continued participation in agility-biased sports and safe execution of multi-directional single-leg hop tests.[41, 42, 116, 147, 154, 221, 227, 238] Evidence that physical activity levels can be recovered and maintained in the presence of isolated knee ligament deficiency supports the notion that mechanical joint instability can be compensated for by sensorimotor control mechanisms including proprioception and neuromuscular control.[19, 70, 115] The findings of previous work and the present study collectively indicate that saggital-plane knee mechanical joint stability alone is not a significant predictor of overall knee functional joint stability defined by the successful performance of multi-directional physical activities. To date, no work has employed objective measurement of knee mechanical joint stability in more than one plane of motion (e.g. saggital plane pus frontal plane) within a correlation or regression design to determine the association of multi-planar mechanical stability on overall knee functional joint stability. The clinical significance of the present results is that ATD as a measure of saggital-plane knee mechanical joint stability may not need to be a major concern within interventions specifically designed to enhance noncontact knee injury prevention and rehabilitation programs.

The timely generation of muscle force as a result of feedback neuromuscular control is important to reduce excessive knee joint displacements and correct knee joint alignment in potential injury situations.[176, 394, 395] In the present research, hamstrings TTPT was retained in the final regression model. As TTPT decreased hop distance increased. This observation is in partial support of Hypothesis 1. To date, no other work has reported the association between TTPT and knee functional joint stability defined by single-leg hop tests in uninjured subjects. One study has reported a significant simple linear regression ($R^2 = 0.31$, $P = 0.00$) between hamstrings TTPT sampled at $240°\cdot\text{sec}^{-1}$ in a 30-90° knee flexion ROM and five meter sprint performance in uninjured subjects.[44] The size of the simple linear regression coefficient is similar to that found in this study (Table 6). The timely generation of muscle force is important for rapidly increasing lower limb joint stiffness,[385] decelerating joint displacements,[176, 394, 395] and enhancing functional performance.[87] Muscles that generate force in a timely manner will be better able to decelerate joint displacement in one direction and then accelerate joint displacement in the opposite direction. With regard to the adapted crossover hop for distance it is evident why hamstrings TTPT can be associated with the distance hopped. The hamstrings are biomechanically capable of limiting excessive tibial displacement relative to the femur in all three planes of motion,[178, 230,

[235] which would be important during the landing phase of each hop. When deceleration of the tibia is complete during the landing phase, the hamstrings can then be a major contributor to the propulsion phase.[216, 288] The clinical significance of this study's findings with regard to hamstrings TTPT being retained as a predictor of knee functional joint stability is that interventions designed to enhance hamstrings TTPT should be considered for inclusion in noncontact knee injury prevention and rehabilitation programs intended to enhance knee functional joint stability defined by multi-directional single-leg hop tests.

Gender and hamstrings TTPT contributed to a final model that significantly predicted 60% of the variance in the adapted crossover hop for distance single-leg hop distance. Based on these results gender and hamstrings TTPT should be considered in the design, development, and evaluation of noncontact knee injury prevention and rehabilitation programs. When using the adapted crossover hop for distance test or any multi-directional single-leg hop test as a measure of knee functional joint stability, comparisons between the genders should be made with careful consideration of the gender-differences in knee mechanical joint stability and sensorimotor control. If the adapted crossover hop for distance test or any multi-directional single-leg hop test is acceptable as a clinical measure of knee functional joint stability, then interventions that target the hamstrings with the intent of reducing TTPT should be included in noncontact knee injury prevention and rehabilitation programs.

5.4.2 Hypothesis 2: Predictors of Single-Leg Stop-Jump Knee Valgus/Varus Displacement

Gender, prone knee extension AJPS, ATD, medial hamstrings preactivity and reactivity, and hamstrings TTPT were examined as potential predictors of the single-leg stop-jump knee valgus/varus displacement. Knee valgus/varus displacement is an important variable when considering knee functional joint stability because a progressive valgus collapse of the knee is the most common mechanism of noncontact knee injury in agility-biased team sports.[38, 39, 208] A progressive valgus collapse of the knee represents a direct manifestation of loss of functional joint stability. Only medial hamstrings reactivity contributed to a final model that significantly predicted 14% of the variance in single-leg stop-jump knee valgus/varus displacement. This result only partially supports Hypothesis 2 since only one of the original six predictor variables was retained in the final equation. The equation indicated that increased medial hamstrings preactivity was associated with knee displacement that progressed in a valgus direction. However, normality screening of raw valgus/varus data and normality diagnostics for valgus/varus regression residuals revealed that data had a non-normal distribution. Linear regression was not, therefore, the appropriate statistical method for analyzing this data. Despite this, the final equation for Hypothesis 2 will now still be briefly discussed as if linear regression was the appropriate method of statistical analysis. The finding that regression analysis was not, in fact, the appropriate statistical method for analyzing this data will be discussed in the next section: Study Limitations.

Females have consistently demonstrated larger values for mean knee valgus kinematics than males during highly dynamic functional tasks.[31, 117, 118, 158, 243, 341, 400] Gender was not associated with knee valgus/varus kinematics as defined in this study. The gender component of Hypothesis 2 was not supported. Of the 44% of subjects that did demonstrate knee valgus displacement during the single-leg stop-jump task, an almost even proportion was evident between males and females. This rudimentary observation alone indicated that a specific gender was not associated with knee displacement in either a valgus or a varus direction. It is unclear why gender was not associated with knee valgus or varus displacement, since the physical activity levels of the subjects recruited for this study was similar to that of subjects recruited for other work.[31, 118, 290] The clinical significance of the present data is that mechanical and or sensorimotor characteristics common to both genders should be considered when designing the content of noncontact knee injury prevention and rehabilitation programs intended to limit knee valgus/varus displacement.

Proprioception is critical for mediating appropriate feedforward and feedback neuromuscular control of functional joint stability.[249, 308, 319] In the current work, prone knee extension AJPS as a measure of hamstrings-biased eccentric-to-isometric proprioception was not retained in the final regression model. The AJPS component of Hypothesis 2 was not supported. There is no published research describing the association between an eccentric-to-isometric hamstrings-biased AJPS test and knee valgus/varus kinematics measured during 3D analyses of single- or double-leg functional tasks. It is not possible, consequently, to directly compare the present findings with any previous work. However, if saggital plane knee kinematics are considered, Nagai et al.[273] reported that knee proprioception defined by flexion and extension TTDPM was significantly associated with favorable knee flexion kinematics during a single-leg stop-jump task.[273] A potential explanation for why AJPS as measured in this study was not associated with knee valgus/varus displacement is that proprioceptive characteristics most relevant to knee valgus/varus displacement were not measured with the prone knee extension test. As stated earlier, it may be that sub-optimal knee proprioceptive function may not be detectable by existing proprioception testing methodologies,[317] and so the size of clinically important proprioceptive differences between limbs or subjects have yet to be identified.[138] The clinical significance of the present finding is that hamstring-biased eccentric-to-isometric proprioception may not be an important component of noncontact knee injury prevention and rehabilitation programs where knee functional joint stability is defined by 3D analyses of knee valgus/varus displacement.

Mechanical joint stability contributes to optimal functional joint stability,[185, 280, 308] and a valid clinical impression regarding an individual's knee functional joint stability cannot be formed unless the status of the individual's knee mechanical joint stability is also known. In this study, ATD was not associated with knee valgus/varus displacement. The ATD component of Hypothesis 2 was not supported. There are no published studies reporting the association between ATD and knee valgus/varus kinematics measured during 3D analyses of single- or double-leg functional tasks. There are no other works, therefore, that the present results can be compared to. The finding that ATD was not associated with valgus/varus displacement as a direct measure of knee functional joint stability is consistent with previous research that reported ATD was also not associated with an indirect measure of knee functional joint stability (e.g. single-leg hop tests, agility-biased running tests, self-report questionnaires).[103, 105, 170, 221, 336, 344] The current study and past studies, together, suggest that knee functional joint stability is not dependent on ATD as a sole measure of knee mechanical joint stability. The clinical significance of the current results is that attention may need to be focused on knee mechanical joint stability in more than one plane of motion when considering the clinically important components of noncontact knee injury prevention and rehabilitation programs.

Feedforward muscle activation (preactivity) is important for increasing preparatory muscle stiffness and enhancing knee functional joint stability.[175, 182, 183, 225, 309] In the present research, medial hamstrings preactivity was associated with knee valgus/varus displacement. However, this finding was not in support of the direction of the association stated in Hypothesis 2. Hypothesis 2 stated that as medial hamstrings preparatory muscle activity increased then knee valgus displacement would decrease: this means the knee was expected to remain in a neutral alignment or displace in a relatively varus direction with increased hamstrings preactivity. Because the valgus direction was designated by a negative sign, and the beta coefficient was of a negative sign, the regression model indicated that increased medial hamstrings preactivity was actually associated with knee displacement that progressed in a valgus direction. This finding was contrary to what was hypothesized, and so an explanation was sought. All subject trials and data processing procedures were meticulously reviewed in their entirety. There appeared to be no errors in EMG data collection, data processing, or data transfer procedures. The present finding of an association between medial hamstrings preactivity and knee valgus displacement is contrary to previous work that showed no association between feedforward activation of the medial hamstrings and knee valgus kinematics.[290] The present finding of an association between medial hamstrings preactivity and a kinematic measure of knee functional joint stability is also contrary to other work that reported no association between medial hamstrings muscle activity 150msec before a specified biomechanical event and a kinetic measure of knee functional joint stability (proximal anterior tibial shear force).[342] Well established empirical data derived from decades of clinical practice has established that an individual can present with selective increased activity (hyperactivity) in a single muscle or muscle group as a result of habitual movement patterns.[228, 289, 328] In those that have not suffered a traumatic injury, the selectively increased muscle activity can be perceived as an adaptation resulting from a single muscle or muscle group up-regulating its activation in order to compensate for sub-optimal activity in another muscle or muscle group.[228, 289, 328] Data derived from laboratory research on injured subjects also shows selectively up-regulated muscle activity in specific lower limb muscles which can be viewed as an adaptation to restrain excessive knee motion in a specific direction and minimize knee joint loading.[130, 284, 322, 364] Clinical and laboratory observations, therefore, demonstrate that the CNS can alter inter-muscular muscle activation patterns in order to facilitate knee functional joint stability and dynamic whole-body movements. With regard to the present research, the increased feedforward activation of the medial hamstrings might be explained as an adaptation to previous long-term experience of high-impact agility-biased physical activities. The increased feedforward medial hamstrings activity is an adaptation designed to limit knee valgus displacement in those individuals that tend to actually demonstrate knee valgus displacement. The CNS may have deliberately and selectively increased feedforward activation of the medial hamstrings to prepare for imminent knee valgus motion and loading with the onset of initial contact during the single-leg stop-jump. The medial hamstrings may have also been selectively activated in individuals that tended to demonstrate knee valgus displacement because other muscles that could have contributed to limiting a dynamic valgus collapse (e.g. gluteus medius, tibialis posterior) were not sufficiently recruited. The clinical significance of the present finding is that feedforward activation of the medial hamstrings needs to be interpreted alongside data on neuromuscular control characteristics of other muscles in the lower limb that are capable of limiting a dynamic valgus collapse during single-leg landing tasks. Informed consideration can then be made regarding the content of noncontact knee injury prevention and rehabilitation programs.

As for feedforward muscle activation, feedback muscle activation can also be important for increasing muscle stiffness and enhancing knee functional joint stability.[223, 225, 308] In the current study, medial hamstrings reactivity was not associated with knee valgus/varus displacement. The medial hamstrings reactivity component of Hypothesis 2 was not supported. There are no published studies reporting the association between medial hamstrings reactivity as defined in this study and knee valgus/varus kinematics measured during 3D analyses of the single-leg stop-jump. There is no other research, therefore, that the present results can be directly compared to. A possible explanation as to why medial hamstrings reactivity was not retained as a predictor of knee valgus/varus displacement is that feedback neuromuscular control of sudden knee joint motion may be too slow to limit excessive knee joint displacement and loading.[225, 297, 395] The timeframe between the onset of joint perturbation and the generation of sufficient muscle stiffness to decelerate and limit the joint perturbation may be too long to prevent injury to the knee's tissues.[225, 297, 395] The clinical significance of the present results is that medial hamstrings preactivity may not be an important component of noncontact knee injury prevention and rehabilitation programs and, therefore, consideration should be given to other neuromuscular control characteristics that may be more influential on knee functional joint stability.

The timely generation of muscle force as a result of feedback neuromuscular control is important to reduce excessive knee joint displacements and correct knee joint alignment in potential injury situations.[176, 394, 395] In this work, hamstrings TTPT was not retained in the final prediction model. The hamstrings TTPT component of Hypothesis 2 was not supported. There is no published research documenting the association between hamstrings TTPT and knee valgus/varus kinematics measured during 3D analysis of single-leg functional tasks. There is no other data, consequently, to which the current study results can be compared.

Only medial hamstrings reactivity contributed to a final model that significantly predicted 14% of the variance in single-leg stop-jump knee valgus/varus displacement. Normality screening of raw valgus/varus data and normality diagnostics for valgus/varus regression residuals revealed, however, that data had a non-normal distribution. Linear regression was not, therefore, the appropriate statistical method for analyzing this data and, based on this statistical model, no clinically meaningful recommendation can be made with regard to the design and development of noncontact knee injury prevention and rehabilitation programs.

5.5 STUDY LIMITATIONS

This study has potential limitations. The speed at which subjects were instructed to perform the prone knee extension AJPS test was “slowly and smoothly”. The instruction “slowly and smoothly” resulted in a low velocity of movement relative to the movement patterns performed during the adapted crossover hop for distance and the single-leg stop-jump. The actual velocity of the prone knee extension AJPS test did not, consequently, approach or match the velocity of knee displacement observed during the adapted crossover hop for distance or the single-leg stop-jump. Extensive pilot testing of the prone knee extension AJPS test revealed that high velocities of movement always resulted in subjects’ inability to decelerate the lower leg before it heavily collided with, and then bounced off, the Thera-Band Tubing of the H-Frame (Figure 7). To ensure reliability and low measurement error of the prone knee extension AJPS test, a low speed of movement was required. The potential impact of performing an eccentric-to-isometric AJPS test at low versus high speeds of movement on the findings of this study is that the prone knee extension AJPS test may not have been sensitive to clinically or statistically important proprioception differences between subjects.

The single-leg stop-jump task did not elicit knee valgus displacement in the majority of subjects. Although the single-leg stop-jump simulates sudden deceleration movement patterns specific to games such as basketball,[31, 273, 337] and has been reported to elicit knee valgus kinematics in athletic subjects,[31, 337] the single-leg stop-jump may not actually reflect athletic tasks most commonly performed during agility-biased team sports.[337] Noncontact knee injuries have been reported as occurring during a variety of different agility-biased tasks,[39, 203, 204, 208, 286] and so more than one laboratory-based functional task may be required to most effectively capture knee valgus displacement data from a study sample. The potential impact of only using the single-leg stop-jump versus a battery of functional tasks is that the single-leg stop-jump alone may not have been able to capture all subjects who demonstrate clinically important knee valgus displacement during athletic maneuvers.

5.6 STUDY SIGNIFICANCE

The results of this study have added potentially valuable information to the literature. Although the core hypotheses were only partially supported, new data has been delivered that expands the existing knowledge-base about local knee characteristics that contribute to knee functional joint stability. The results of this study may, therefore, offer a foundation for future research that further contributes to the design and development of more effective and efficient noncontact knee injury prevention, injury rehabilitation, and performance optimization programs.

5.6.1 Hypothesis 1

The results of this study revealed that gender and hamstrings TTPT contributed to a final model that significantly predicted 60% of the variance in the adapted crossover hop for distance single-leg hop distance. The data only partially supported Hypothesis 1 since two of the original four predictor variables were retained in the final equation. The data indicated that males would hop further than females, and that as TTPT decreased hop distance would increase. The clinical significance of the finding that AJPS and ATD were not retained in the final equation is that hamstrings-biased eccentric-to-isometric proprioception and saggital-plane knee mechanical joint stability may not need to be major considerations in the design and development of noncontact knee injury control programs. The clinical significance of the gender finding is that if the adapted crossover hop for distance is to be used as a clinical and indirect measure of knee functional joint stability, a female athlete's performance of the adapted crossover hop for distance should not be interpreted solely in comparison to that of a male athlete's performance. A female athlete's performance of single-leg hop tests should be carefully interpreted in line with what is known about female-specific mechanical joint stability, proprioception, neuromuscular control, and biomechanical characteristics. The clinical significance of the hamstrings TTPT finding is that interventions designed to enhance hamstrings TTPT should be considered for inclusion in noncontact knee injury prevention and rehabilitation programs intended to enhance knee functional joint stability defined by multi-directional single-leg hop tests. The inclusion of specific interventions in intervention programs can then be further justified and validated according to their ability to beneficially enhance the clinical outcomes of knee injury prevention and rehabilitation programs.[221, 339]

5.6.2 Hypothesis 2

The results of this study also revealed that the majority of subjects performed the single-leg stop-jump with knee varus versus knee valgus displacement and that outcome variable and residuals data was not normally distributed. Multiple linear regression was not, therefore, the appropriate statistical method for analyzing the present data. Based on the variables employed in this study and a multiple linear regression statistical model, no clinically meaningful recommendation can be made at this time with regard to the design and development of noncontact knee injury prevention and rehabilitation programs. The clinical significance of the finding that the majority of subjects performed the single-leg stop-jump with knee varus versus knee valgus displacement is, however, that more than one functional task may be required to capture knee valgus displacement data. The use of more than one functional task may then provide a more comprehensive kinematic profile for the knee that better captures data from all subjects who demonstrate clinically important knee valgus displacement during athletic maneuvers.

5.7 FUTURE RESEARCH DIRECTIONS

Further research directed at identifying predictors of knee functional joint stability can potentially use the limitations and findings of the present work to guide future study design. Based on the findings for Hypothesis 1, AJPS was not retained in the final equation. This may be because the prone knee extension AJPS test was not sensitive to clinically or statistically important proprioception differences between subjects. In light of this finding, future studies might consider designing and employing new tests of proprioception that are sensitive enough to establish minimal clinically important differences in joint position sense, kinesthesia, and force sense.[138, 317] Tests of proprioception must be designed and developed with careful consideration of the underlying neurophysiological mechanisms and the specific variable that is extracted from the test for use in statistical analyses.[310] The design and development of such tests may then yield additional data that can be usefully employed as a predictor variable in correlation and multivariate study designs that seek to identify the relative contribution of various components of proprioception to knee functional joint stability.

Based on the data collected for Hypothesis 2, the majority of subjects in this study did not demonstrate knee valgus displacement during the single-leg stop-jump and knee valgus/varus displacement data was not normally distributed. In light of these observations, future studies might consider employing more than one laboratory-based functional task that simulates sports-specific movement patterns and the mechanisms of noncontact knee injury; outcome variables could then be extracted from the tasks' raw data to serve as operational definitions for the direct measurement of knee functional joint stability (e.g. knee valgus displacement). Employing more than one functional task (e.g. directionality of task (vertical/lateral double-leg stop-jump); type of task (double-leg stop-jump vs. double-leg drop-landing)) offers the potential to capture different kinematic profiles in the same plane of motion across tasks.[339, 341] Capturing different kinematic profiles in the same plane of motion across tasks may build a more comprehensive overall kinematic profile of the knee, potentially offering the opportunity to identify clinically important knee valgus displacement in a larger proportion of subjects forming a study sample. Employing more than one functional task to more thoroughly identify proportions of subjects that demonstrate clinically meaningful physical characteristics relevant to knee functional joint stability is a research approach previously applied in the single-leg hop testing literature.[4, 20, 277]

5.8 CONCLUSION

The purpose of this study was to determine the extent to which gender and measures of knee mechanical joint stability, proprioception, and neuromuscular control predicted knee functional joint stability. Two hypotheses were examined using multiple linear regression models, each hypothesis with a specific operational definition of knee functional joint stability as the outcome variable: 1. single-leg hop distance for the adapted crossover hop for distance test; 2. total knee valgus displacement for the single-leg stop-jump test. For Hypothesis 1, the hypothesis was partially supported because gender and hamstrings TTPT contributed to a final model that significantly predicted 60% of the variance in the adapted crossover hop for distance single-leg hop distance. Based on these results, gender and hamstrings TTPT should be considered in the design, development, and evaluation of noncontact knee injury prevention and rehabilitation programs. For Hypothesis 2, no clinically useful statistical model could be built because outcome variable raw data and the final equation's residuals proved to have a non-normal distribution. Based on these results, future research might consider employing more than one laboratory-based sports-specific functional task from which kinematic outcome variables can be extracted to serve as operational definitions for the direct measurement of knee functional joint stability.

APPENDIX

NOYES’ KNEE SPORTS ACTIVITY RATING SCALE

Check the box which best describes your current level of exercise/sports activity

	Current Level	Level I (participates 4-7 days/week)
100	☐	Jumping, hard pivoting, cutting (basketball, volleyball, football, gymnastics, soccer)
95	☐	Running, twisting, turning (tennis, racquetball handball, ice hockey, skiing, wrestling)
90	☐	No running, twisting, jumping (cycling, swimming)
		Level II (participates 1-3 days/week)
85	☐	Jumping, hard pivoting, cutting (basketball, volleyball, football, gymnastics, soccer)
80	☐	Running, twisting, turning (tennis, racquetball handball, ice hockey, skiing, wrestling)
75	☐	No running, twisting, jumping (cycling, swimming)
		Level III (participates 1-3 times/month)
65	☐	Jumping, hard pivoting, cutting (basketball, volleyball, football, gymnastics, soccer)
60	☐	Running, twisting, turning (tennis, racquetball handball, ice hockey, skiing, wrestling)
55	☐	No running, twisting, jumping (cycling, swimming)
		Level IV (no sports)
40	☐	I perform activities of daily living without problems
20	☐	I have moderate problems with activities of daily living
0	☐	I have severe problems with daily living (on crutches, full disability)

BIBLIOGRAPHY

1. Aagaard P, Simonsen E, Andersen J, Magnusson P, Dyhre-Poulsen P. Increased rate of force development and neural drive of human skeletal muscle following resistance training. *J Appl Physiol.* 2002;93(4):1318-1326.

2. Abt J, Sell T, Laudner K, et al. Neuromuscular and biomechanical characteristics do not vary across the menstrual cycle. *Knee Surg Sports Traumatol Arthrosc.* 2007;15(7):901-907.

3. Ageberg E, Fridén T. Normalized motor function but impaired sensory function after unilateral non-reconstructed ACL injury: patients compared with uninjured controls. *Knee Surg Sports Traumatol Arthrosc.* 2008;16(5):449-456.

4. Ageberg E, Thomeé R, Neeter C, Silbernagel K, Roos E. Muscle strength and functional performance in patients with anterior cruciate ligament injury treated with training and surgical reconstruction or training only: a two to five-year followup. *Arthritis Rheum.* 2008;59(12):1773-1779.

5. Agel J, Arendt E, Bershadsky B. Anterior cruciate ligament injury in national collegiate athletic association basketball and soccer: a 13-year review. *Am J Sports Med.* 2005;33(4):524-530.

6. Agel J, Evans T, Dick R, Putukian M, Marshall S. Descriptive epidemiology of collegiate men's soccer injuries: National Collegiate Athletic Association Injury Surveillance System, 1988-1989 through 2002-2003. *J Athl Train.* 2007;42(2):270-277.

7. Agel J, Olson D, Dick R, Arendt E, Marshall S, Sikka R. Descriptive epidemiology of collegiate women's basketball injuries: National Collegiate Athletic Association Injury Surveillance System, 1988-1989 through 2003-2004. *J Athl Train.* 2007;42(2):202-210.

8. Akins J, Longo P, Bertoni M, et al. Postural stability and isokinetic strength do not predict knee valgus angle during single-leg drop-landing or single-leg squat in elite male rugby union players. *Isokinetics Exercise Science.* 2013;21(1):37-46.

9. Albert M. *Eccentric Muscle Training in Sports and Orthopaedics*. London: Churchill Livingstone; 1995.

10. Alentorn-Geli E, Myer G, Silvers H, et al. Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: Mechanisms of injury and underlying risk factors. *Knee Surg Sports Traumatol Arthrosc.* 2009;17(7):705-729.

11. Ambu. Ambu. Available at: http://www.ambu.com/corp/home.aspx, 2013.

12. Andersen SB, Terwilliger DM, Denegar CR. Comparison of open versus closed kinetic chain test positions for measuring joint position sense. *J Sport Rehabil.* 1995;4:165-171.

13. Andriacchi T. Dynamics of knee malalignment. *Orthop Clin North Am.* 1994;25(3):395-403.

14. Andriacchi T, Andersson G, Ortengren R, Mikosz R. A study of factors influencing muscle activity about the knee joint. *J Orthop Res.* 1984;1(3):266-275.

15. Arendt E, Dick R. Knee injury patterns among men and women in collegiate basketball and soccer. NCAA data and review of literature. *Am J Sports Med.* 1995;23(6):694-701.

16. Baker V, Bennell K, Stillman B, Cowan S, Crossley K. Abnormal knee joint position sense in individuals with patellofemoral pain syndrome. *J Orthop Res.* 2002;20(2):208-214.

17. Ballantyne B, French A, Heimsoth S, Kachingwe A, Lee J, Soderberg G. Influence of examiner experience and gender on interrater reliability of KT-1000 arthrometer measurements. *Phys Ther.* 1995;75(10):898-906.

18. Barber-Westin S, Noyes F, McCloskey J. Rigorous statistical reliability, validity, and responsiveness testing of the Cincinnati knee rating system in 350 subjects with uninjured, injured, or anterior cruciate ligament-reconstructed knees. *Am J Sports Med.* 1999;27(4):402-416.

19. Barber S, Noyes F, Mangine R, DeMaio M. Rehabilitation after ACL reconstruction: function testing. *Orthopedics.* 1992;15(8):969-974.

20. Barber S, Noyes F, Mangine R, McCloskey J, Hartman W. Quantitative assessment of functional limitations in normal and anterior cruciate ligament-deficient knees. *Clin Orthop Relat Res.* 1990(255):204-214.

21. Barrack R, Lund P, Skinner H. Knee joint proprioception revisited. *J Sport Rehabil.* 1994;3(1):18-42.

22. Barrack R, Skinner H. The sensory function of knee ligaments. In: Daniel D, Akeson W, O'Connor J, eds. *Knee Ligaments. Structure, Function, Injury, and Repair*. New York: Raven Press; 1990:95-114.

23. Barrack R, Skinner H, Buckley S. Proprioception in the anterior cruciate deficient knee. *Am J Sports Med.* 1989;17(1):1-6.

24. Basmajian J, De Luca C. *Muscles Alive. Their Functions Revealed by Electromyography*. 5th ed. Baltimore: Williams and Wilkins; 1985.

25. Beard D, Dodd C, Trundle H, Simpson A. Proprioception enhancement for anterior cruciate ligament deficiency. A prospective randomised trial of two physiotherapy regimes. *J Bone Joint Surg Br.* 1994;76(4):654-659.

26. Beard D, Kyberd P, Fergusson C, Dodd C. Proprioception after rupture of the anterior cruciate ligament. An objective indication of the need for surgery? *J Bone Joint Surg Br.* 1993;75(2):311-315.

27. Beard D, Kyberd P, O'Connor J, Fergusson C, Dodd C. Reflex hamstring contraction latency in anterior cruciate ligament deficiency. *J Orthop Res.* 1994;12(2):219-228.

28. Behm DG. Neuromuscular implications and applications of resistance training. *J Strength Cond Res.* 1995;9(4):264-274.

29. Bell D, Jacobs I. Electro-mechanical response times and rate of force development in males and females. *Med Sci Sports Exerc.* 1986;18(1):31-36.

30. Benjaminse A. *Reliability and Precision of Hip Proprioception Methods in Healthy Individuals* [MS Dissertation]. Pittsburgh: Department of Sports Medicine and Nutrition, University of Pittsburgh; 2008.

31. Benjaminse A, Habu A, Sell T, et al. Fatigue alters lower extremity kinematics during a single-leg stop-jump task. *Knee Surg Sports Traumatol Arthrosc.* 2008;16(4):400-407.

32. Bennell K, Wee E, Crossley K, Stillman B, Hodges P. Effects of experimentally-induced anterior knee pain on knee joint position sense in healthy individuals. *J Orthop Res.* 2005;23(1):46-53.

33. Berns GS, Hull M, Patterson HA. Strain in the anteromedial bundle of the anterior cruciate ligament under combination loading. *J Orthop Res.* 1992;10(2):167-176.

34. Berryman Reese N, Bandy W. *Joint Range of Motion and Muscle Length Testing*. 2nd ed. Missouri: Saunders Elsevier; 2010.

35. Besier T, Lloyd D, Ackland T. Muscle activation strategies at the knee during running and cutting maneuvers. *Med Sci Sports Exerc.* 2003;35(1):119-127.

36. Biodex. Biodex. Available at: http://www.biodex.com/physical-medicine/products/dynamometers. Accessed July, 2012.

37. Birmingham T, Kramer J, Inglis J, et al. Effect of a neoprene sleeve on knee joint position sense during sitting open kinetic chain and supine closed kinetic chain tests. *Am J Sports Med.* 1998;26(4):562-566.

38. Boden B, Dean G, Feagin J, Garrett W. Mechanisms of anterior cruciate ligament injury. *Orthopedics.* 2000;23(6):573-578.

39. Boden B, Sheehan F, Torg J, Hewett T. Noncontact anterior cruciate ligament injuries: mechanisms and risk factors. *J Am Acad Orthop Surg.* 2010;18(9):520-527.

40. Boden B, Torg J, Knowles S, Hewett T. Video analysis of anterior cruciate ligament injury: abnormalities in hip and ankle kinematics. *Am J Sports Med.* 2009;37(2):252-259.

41. Borsa P, Lephart S, Irrgang J. Comparison of performance-based and patient-reported measures of function in anterior-cruciate-ligament-deficient individuals. *J Orthop Sp Phys Ther.* 1998;28(6):392-399.

42. Borsa P, Lephart S, Irrgang J, Safran M, Fu F. The effects of joint position and direction of joint motion on proprioceptive sensibility in anterior cruciate ligament-deficient athletes. *Am J Sports Med.* 1997;25(3):336-340.

43. Borsa P, Sauers E, Lephart S. Functional training for the restoration of dynamic stability in the PCL-injured knee. *J Sport Rehab.* 1999;8:362-378.

44. Bračič M, Hadžič V, Čoh M, Dervišević E. Relationship between time to peak torque of hamstrings and sprint running performance. *Isokinetics Exercise Science.* 2011;19(4):281-286.

45. Brindle T, Mizelle J, Lebiedowska M, Miller J, Stanhope S. Visual and proprioceptive feedback improves knee joint position sense. *Knee Surg Sports Traumatol Arthrosc.* 2009;17(1):40-47.

46. Brooks J, Fuller C, Kemp S, Reddin D. Epidemiology of injuries in English professional rugby union: part 1 match injuries. *Br J Sports Med.* 2005;39(10):757-766.

47. Brooks J, Fuller C, Kemp S, Reddin D. Epidemiology of injuries in English professional rugby union: part 2 training Injuries. *Br J Sports Med.* 2005;39(10):767-775.

48. Brosky J, Nitz A, Malone T, Caborn D, Rayens M. Intrarater reliability of selected clinical outcome measures following anterior cruciate ligament reconstruction. *J Orthop Sp Phys Ther.* 1999;29(1):39-48.

49. Brosseau L, Tousignant M, Budd J, et al. Intratester and intertester reliability and criterion validity of the parallelogram and universal goniometers for active knee flexion in healthy subjects. *Physiother Res Int.* 1997;2(3):150-166.

50. Brown L. *Isokinetics in Human Performance*: Human Kinetics Publishers; 2000.

51. Brown L, Ferrigno V. *Training for Speed, Agility, and Quickness*. Illinois: Human Kinetics; 2005.

52. Brown L, Weir J. ASEP procedures recommendation I: accurate assessment of muscular strength and power. *J Exerc Physiol.* 2001;4(3):1-21.

53. Brown T, McLean S, Palmieri-Smith R. Associations between lower limb muscle activation strategies and resultant multi-planar knee kinetics during single-leg landings. *J Sci Med Sport.* 2013;In press.

54. Buchanan T, Kim A, Lloyd D. Selective muscle activation following rapid varus/valgus perturbations at the knee. *Med Sci Sports Exerc.* 1996;28(7):870-876.

55. Buchner A, Faul F, Erdfelder E, Dilger S, Bredenkamp J. G*Power 3. Available at: http://www.psycho.uni-duesseldorf.de/aap/projects/gpower/. Accessed July, 2012.

56. Butler D, Noyes F, Grood E. Ligamentous restraints to anterior-posterior drawer in the human knee. A biomechanical study. *J Bone Joint Surg Am.* 1980;62(2):259-270.

57. Callaghan M, Selfe J, Bagley P, Oldham J. The effects of patellar taping on knee joint proprioception. *J Athl Train.* 2002;37(1):19-24.

58. Callaghan M, Selfe J, McHenry A, Oldham J. Effects of patellar taping on knee joint proprioception in patients with patellofemoral pain syndrome. *Man Ther.* 2008;13(3):192-199.

59. Carter N, Jenkinson T, Wilson D, Jones D, Torode A. Joint position sense and rehabilitation in the anterior cruciate ligament deficient knee. *Br J Sports Med.* 1997;31(3):209-212.

60. Chan K, Maffulli N, Korkia P, Li R. *Principles and Practice of Isokinetics in Sports Medicine and Rehabilitation*. Hong Kong: Williams and Wilkins; 1996.

61. Chan Y. Biostatistics 104: correlational analysis. *Singapore Med J.* 2003;44(12):614-619.

62. Chang A, Hayes K, Dunlop D, et al. Hip abduction moment and protection against medial tibiofemoral osteoarthritis progression. *Arthritis Rheum.* 2005;52(11):3515-3519.

63. Chappell J, Creighton R, Giuliani C, Yu B, Garrett W. Kinematics and electromyography of landing preparation in vertical stop-jump: risks for noncontact anterior cruciate ligament injury. *Am J Sports Med.* 2007;35(2):235-241.

64. Chappell J, Yu B, Kirkendall D, Garrett W. A comparison of knee kinetics between male and female recreational athletes in stop-jump tasks. *Am J Sports Med.* 2002;30(2):261-267.

65. Chaterjee S, Hadi A. *Regression Analysis by Example*. 4th ed. New York: John Wiley and Sons; 2006.

66. Chmielewski T, Jones D, Day T, Tillman S, Lentz T, George S. The association of pain and fear of movement/reinjury with function during anterior cruciate ligament reconstruction rehabilitation. *J Orthop Sp Phys Ther.* 2008;38(12):746-753.

67. Chu Y, Sell T, Abt J, et al. Air assault soldiers demonstrate more dangerous landing biomechanics when visual input is removed. *Mil Med.* 2012;177(1):41-47.

68. Claiborne T, Armstrong C, Gandhi V, Pincivero D. Relationship between hip and knee strength and knee valgus during a single leg squat. *J Appl Biomech.* 2006;22(1):41-50.

69. Clapper MP, Wolf SL. Comparison of the reliability of the Orthoranger and the standard goniometer for assessing active lower extremity range of motion. *Phys Ther.* 1988;68(2):214-218.

70. Clark N. Functional performance testing following knee ligament injury. *Phys Ther Sp.* 2001;2:91-105.

71. Clark N. Relationship between active hamstring stretch reflex latency and functional knee stability. *2nd International Conference on Movement Dysfunction. Pain and Performance: Evidence and Effect*. Edinburgh, Scotland: Kinetic Control/Manipulation Association of Chartered Physiotherapists; 2005.

72. Clark N, Gumbrell C, Rana S, Traloe C. *The correlation of short-term clinical measures after anterior cruciate ligament reconstruction to long-term outcome*. London: Department of Health Sciences, University of East London; 1999.

73. Clark N, Gumbrell C, Rana S, Traole C, Morrissey M. Intratester reliability and measurement error of the adapted crossover hop for distance. *Phys Ther Sp.* 2002;3(3):143-151.

74. Clark N, Herrington L. The knee. In: Comfort P, Abrahamson E, eds. *Sports Rehabilitation and Injury Prevention*. Oxford: Wiley-Blackwell; 2010:407-463.

75. Clark N, Sell T, Keenan K, Lephart S. Injury prevention and rehabilitation: In press; 2012.

76. Cook C, McDonagh M. Measurement of muscle and tendon stiffness in man. *Eur J Appl Physiol.* 1996;72(4):380-382.

77. Cumps E, Verhagen E, Annemans L, Meeusen R. Injury rate and socioeconomic costs resulting from sports injuries in Flanders: data derived from sports insurance statistics 2003. *Br J Sports Med.* 2008;42(9):767-772.

78. Dallalana R, Brooks J, Kemp S, Williams A. The epidemiology of knee injuries in English professional rugby union. *Am J Sports Med.* 2007;35(5):818-830.

79. Daniel D, Malcom L, Losse G, Stone M, Sachs R, Burks R. Instrumented measurement of anterior laxity of the knee. *J Bone Joint Surg Am.* 1985;67(5):720-726.

80. Daniel D, Stone M, Dobson B, Fithian D, Rossman D, Kaufman K. Fate of the ACL-injured patient. A prospective outcome study. *Am J Sports Med.* 1994;22(5):632-644.

81. Daniel D, Stone M, Sachs R, Malcom L. Instrumented measurement of anterior knee laxity in patients with acute anterior cruciate ligament disruption. *Am J Sports Med.* 1985;13(6):401-407.

82. Davis R, Ounpuu S, Tyburski D, Gage J. A giat analysis data collection and reduction technique. *Human Movement Science.* 1991;10:575-587.

83. Day B, Mackenzie W, Shim S, Leung G. The vascular and nerve supply of the human meniscus. *Arthroscopy.* 1985;1(1):58-62.

84. de Loës M, Dahlstedt L, Thomée R. A 7-year study on risks and costs of knee injuries in male and female youth participants in 12 sports. *Scand J Med Sci Sports.* 2000;10(2):90.

85. De Luca C. The use of surface electromyography in biomechanics. *J Appl Biomech.* 1997;13(2):135-163.

86. De Luca G. Fundamental Concepts in EMG Signal Acquisition. Natick, MA: Delsys, Inc.; 2001.

87. de Ruiter C, de Korte A, Schreven S, de Haan A. Leg dominancy in relation to fast isometric torque production and squat jump height. *Eur J Appl Physiol.* 2010;108(2):247-255.

88. Decker M, Torry M, Wyland D, Sterett W, Steadman J. Gender differences in lower extremity kinematics, kinetics and energy absorption during landing. *Clin Biomech.* 2003;18:662-669.

89. Delp S, Hess W, Hungerford D, Jones L. Variation of rotation moment arms with hip flexion. *J Biomech.* 1999;32(5):493-501.

90. DeMont R, Lephart S. Effect of sex on preactivation of the gastrocnemius and hamstring muscles. *Br J Sports Med.* 2004;38(2):120-124.

91. DeMont R, Lephart S, Giraldo J, Swanik C, Fu F. Muscle preactivity of anterior cruciate ligament-deficient and-reconstructed females during functional activities. *J Athl Train.* 1999;34(2):115-120.

92. Dhaher Y, Tsoumanis A, Houle T, Rymer W. Neuromuscular reflexes contribute to knee stiffness during valgus loading. *J Neurophysiol.* 2005;93(5):2698-2709.

93. Di Fabio R. Reliability of computerized surface electromyography for determining the onset of muscle activity. *Phys Ther.* 1987;67(1):43-48.

94. Dick R, Agel J, Marshall SW. National Collegiate Athletic Association injury surveillance system commentaries: introduction and methods. *J Athl Train.* 2007;42(2):173-182.

95. Dick R, Hertel J, Agel J, Grossman J, Marshall SW. Descriptive epidemiology of collegiate men's basketball injuries: National Collegiate Athletic Association Injury Surveillance System, 1988–1989 through 2003–2004. *J Athl Train.* 2007;42(2):194-201.

96. Dick R, Putukian M, Agel J, Evans TA, Marshall SW. Descriptive epidemiology of collegiate women's soccer injuries: National Collegiate Athletic Association Injury Surveillance System, 1988–1989 through 2002–2003. *J Athl Train.* 2007;42(2):278-285.

97. Docherty C, Moore J, Arnold B. Effects of strength training on strength development and joint position sense in functionally unstable ankles. *J Athl Train.* 1998;33(4):310-314.

98. Drouin J, Valovich-mcLeod T, Shultz S, Gansneder B, Perrin D. Reliability and validity of the Biodex system 3 pro isokinetic dynamometer velocity, torque and position measurements. *Eur J Appl Physiol.* 2004;91(1):22-29.

99. Drouin JM, Houglum PA, Perrin DH, Gansneder BM. Weight-bearing and non-weight-bearing knee-joint reposition sense and functional performance. *J Sport Rehabil.* 2003;12(1):54-66.

100. Duncan A, McDonagh M. Stretch reflex distinguished from pre-programmed muscle activations following landing impacts in man. *J Physiol.* 2000;526:457-468.

101. Dyhre-Poulsen P, Krogsgaard M. Muscular reflexes elicited by electrical stimulation of the anterior cruciate ligament in humans. *J Appl Physiol.* 2000;89(6):2191-2195.

102. Dyhre-Poulsen P, Simonsen E, Voigt M. Dynamic control of muscle stiffness and H reflex modulation during hopping and jumping in man. *J Physiol.* 1991;437:287-304.

103. Eastlack M, Axe M, Snyder-Mackler L. Laxity, instability, and functional outcome after ACL injury: copers versus noncopers. *Med Sci Sports Exerc.* 1999;31(2):210-215.

104. Eitzen I, Moksnes H, Snyder-Mackler L, Engebretsen L, Risberg M. Functional tests should be accentuated more in the decision for ACL reconstruction. *Knee Surg Sports Traumatol Arthrosc.* 2010;18(11):1517-1525.

105. Elmlinger B, Nyland J, Tillett E. Knee flexor function 2 years after anterior cruciate ligament reconstruction with semitendinosus-gracilis autografts. *Arthroscopy.* 2006;22(6):650-655.

106. Enoka R. Neuromechanics of Human Movement. 3rd ed. Illinois: Human Kinetics; 2002.

107. Escamilla R, Fleisig G, Zheng N, Barrentine S, Wilk K, Andrews J. Biomechanics of the knee during closed kinetic chain and open kinetic chain exercises. *Med Sci Sports Exerc.* 1998;30(4):556-569.

108. Evans C, Fellows S, Rack P, Ross H, Walters D. Response of the normal human ankle joint to imposed sinusoidal movements. *J Physiol.* 1983;344:483-502.

109. Faude O, Junge A, Kindermann W, Dvorak J. Injuries in Female Soccer Players. *Am J Sports Med.* 2005;33:1694-1700.

110. Ferrell W, Nade S, Newbold P. The interrelation of neural discharge, intra-articular pressure, and joint angle in the knee of the dog. *J Physiol.* 1986;373:353-365.

111. FIBA. Fédération Internationale de Basketball - About FIBA: International Basketball Federation. Available at: http://www.fiba.com/pages/eng/fc/FIBA/quicFact/p/openNodeIDs/962/selNodeID/962/quicFacts.html. Accessed 22 September, 2012.

112. FIFA. Fédération Internationale de Football Association - FIFA Association. Available at: http://www.fifa.com/aboutfifa/organisation/associations.html. Accessed 22 September, 2012.

113. Fitzgerald G. Open versus closed kinetic chain exercise: issues in rehabilitation after anterior cruciate ligament reconstructive surgery. *Phys Ther.* 1997;77(12):1747-1754.

114. Fitzgerald G, Axe M, Snyder-Mackler L. A decision-making scheme for returning patients to high-level activity with nonoperative treatment after anterior cruciate ligament rupture. *Knee Surg Sports Traumatol Arthrosc.* 2000;8(2):76-82.

115. Fitzgerald G, Lephart S, Hwang J, Wainner R. Hop tests as predictors of dynamic knee stability. *J Orthop Sports Phys Ther.* 2001;31(10):588-597.

116. Fontboté C, Sell T, Laudner K, et al. Neuromuscular and biomechanical adaptations of patients with isolated deficiency of the posterior cruciate ligament. *Am J Sports Med.* 2005;33(7):982-989.

117. Ford K, Myer G, Hewett T. Valgus knee motion during landing in high school female and male basketball players. *Med Sci Sports Exerc.* 2003;35(10):1745-17450.

118. Ford K, Myer G, Smith R, Vianello R, Seiwert S, Hewett T. A comparison of dynamic coronal plane excursion between matched male and female athletes when performing single leg landings. *Clin Biomech.* 2006;21(1):33-40.

119. Ford L, Huxley A, Simmons R. Tension transients during steady shortening of frog muscle fibres. *J Physiol.* 1985;361:131-150.

120. Ford L, Huxley A, Simmons R. Tension transients during the rise of tetanic tension in frog muscle fibres. *J Physiol.* 1986;372:595-609.

121. Forthofer R, Lee E, Hernanadez M. *Biostatistics*. 2nd ed. Amsterdam: Elsevier; 2007.

122. Freedman K, Glasgow M, Glasgow S, Bernstein J. Anterior cruciate ligament injury and reconstruction among university students. *Clin Orthop Relat Res.* 1998(356):208-212.

123. Freeman M. Instability of the foot after injuries to the lateral ligament of the ankle. *J Bone Joint Surg Br.* 1965;47(4):669-677.

124. Freeman M, Dean M, Hanham I. The etiology and prevention of functional instability of the foot. *J Bone Joint Surg Br.* 1965;47(4):678-685.

125. Fridén T, Roberts D, Movin T, Wredmark T. Function after anterior cruciate ligament injuries. Influence of visual control and proprioception. *Acta Orthop Scan.* 1998;69(6):590-594.

126. Fridén T, Roberts D, Zätterström R, Lindstrand A, Moritz U. Proprioception in the nearly extended knee. Measurements of position and movement in healthy individuals and in symptomatic anterior cruciate ligament injured patients. *Knee Surg Sports Traumatol Arthrosc.* 1996;4(4):217-224.

127. Friemert B, Faist M, Spengler C, Gerngross H, Claes L, Melnyk M. Intraoperative direct mechanical stimulation of the anterior cruciate ligament elicits short-and medium-latency hamstring reflexes. *J Neurophysiol.* 2005;94(6):3996-4001.

128. Fukuda Y, Woo S, Loh J, et al. A quantitative analysis of valgus torque on the ACL: a human cadaveric study. *J Orthop Res.* 2003;21(6):1107-1112.

129. Gandevia S, McCloskey D, Burke D. Kinaesthetic signals and muscle contraction. *Trends Neurosci.* 1992;15(2):62-65.

130. Gauffin H, Tropp H. Altered movement and muscular-activation patterns during the one-legged jump in patients with an old anterior cruciate ligament rupture. *Am J Sports Med.* 1992;20(2):182-192.

131. Gelber A, Hochberg M, Mead L, Wang N, Wigley F, Klag M. Joint injury in young adults and risk for subsequent knee and hip osteoarthritis. *Ann Intern Med.* 2000;133:321-328.

132. Ghez C. The cerebellum. In: Kandel E, Schwartz J, Jessell T, eds. *Principles of Neural Science*. 3rd ed. London: Prentice-Hall International Inc.; 1991:626-646.

133. Ghez C. The control of movement. In: Kandel E, Schwartz J, Jessell T, eds. *Principles of Neural Science*. 3rd ed. London: Prentice-Hall International Inc.; 1991:533-547.

134. Ghez C. Posture. In: Kandel E, Schwartz J, Jessell T, eds. *Principles of Neural Science*. 3rd ed. London: Prentice-Hall International Inc; 1991:596-607.

135. Ghez C. Voluntary movement. In: Kandel E, Schwartz J, Jessell T, eds. *Principles of Neural Science*. 3rd ed. London: Prentice-Hall International Inc.; 1991:609-625.

136. Ghiasi F, Akbari A. Comparison of the effects of open and closed kinematic chain and different target positions on the knee joint position sense. *J Med Sci.* 2007;7(6):969-976.

137. Gilmore K, Meyers J. Using surface electromyography in physiotherapy research. *Aust J Physiother.* 1983;29(1):3-9.

138. Gokeler A, Benjaminse A, Hewett T, et al. Proprioceptive deficits after ACL injury: are they clinically relevant? *Br J Sports Med.* 2011;46(3):180-192.

139. Gordon J, Ghez C. Muscle receptors and spinal reflexes: The stretch reflex. In: Kandel E, Schwartz J, Jessell T, eds. *Principles of Neural Science*. 3rd ed. London: Prentice-Hall International; 1991:564-580.

140. Gottlob C, Baker Jr C. Anterior cruciate ligament reconstruction: socioeconomic issues and cost effectiveness. *Am J Orthop.* 2000;29(6):472-476.

141. Gottlob C, Baker Jr C, Pellissier J, Colvin L. Cost effectiveness of anterior cruciate ligament reconstruction in young adults. *Clin Orthop Relat Res.* 1999(367):272-282.

142. Greenberger H, Paterno M. Relationship of knee extensor strength and hopping test performance in the assessment of lower extremity function. *J Orthop Sp Phys Ther.* 1995;22(5):202-206.

143. Greenfield M, Kuhn J, Wojtys E. A statistics primer. Correlation and regression analysis. *Am J Sports Med.* 1998;26(2):338-343.

144. Gregory J, Wise A, Wood S, Prochazka A, Proske U. Muscle history, fusimotor activity and the human stretch reflex. *J Physiol.* 1998;513(Pt 3):927-934.

145. Griffin L, Agel J, Albohm M, et al. Noncontact anterior cruciate ligament injuries: risk factors and prevention strategies. *J Am Acad Orthop Surg.* 2000;8(3):141-150.

146. Griffin L, Albohm M, Arendt E, et al. Understanding and preventing noncontact anterior cruciate ligament injuries: a review of the Hunt Valley II meeting, January 2005. *Am J Sports Med.* 2006;34(9):1512-1532.

147. Grindem H, Logerstedt D, Eitzen I, et al. Single-legged hop tests as predictors of self-reported knee function in nonoperatively treated individuals with anterior cruciate ligament injury. *Am J Sports Med.* 2011;39(11):2347-2354.

148. Grood E, Noyes F, Butler D, Suntay W. Ligamentous and capsular restraints preventing straight medial and lateral laxity in intact human cadaver knees. *J Bone Joint Surg Am.* 1981;63(8):1257-1269.

149. Gruber M, Gruber S, Taube W, Schubert M, Beck S, Gollhofer A. Differential effects of ballistic versus sensorimotor training on rate of force development and neural activation in humans. *J Strength Cond Res.* 2007;21(1):274-282.

150. Guyatt G, Walter S, Shannon H, Cook D, Jaeschke R, Heddle N. Basic statistics for clinicians: 4. Correlation and regression. *CMAJ.* 1995;152(4):497-504.

151. Harman E. Principles of test selection and administration. In: Baechle T, Earle R, eds. *Essentials of Strength Training and Conditioning*. 3rd ed. Illinois: Human Kinetics; 2008:237-247.

152. Harman E, Garhammer J. Administration, scoring, and interpretation of selected tests. In: Baechle T, Earle R, eds. *Essentials of Strength Training and Conditioning*. Illinois: Human Kinetics; 2008:249-292.

153. Hart J, Garrison J, Kerrigan D, Palmieri-Smith R, Ingersoll C. Gender differences in gluteus medius muscle activity exist in soccer players performing a forward jump. *Res Sports Med.* 2007;15:147-155.

154. Hartigan E, Axe M, Snyder-Mackler L. Time line for noncopers to pass return-to-sports criteria after anterior cruciate ligament reconstruction. *J Orthop Sp Phys Ther.* 2010;40(3):141-154.

155. Hefti F, Müller W, Jakob R, Stäubli H. Evaluation of knee ligament injuries with the IKDC form. *Knee Surg Sports Traumatol Arthrosc.* 1993;1(3-4):226-234.

156. Herrington L. The effects of 4 weeks of jump training on landing knee valgus and crossover hop performance in female basketball players. *J Strength Cond Res.* 2010;24(12):3427-3432.

157. Herrington L. Knee valgus angle during landing tasks in female volleyball and basketball players. *J Strength Cond Res.* 2011;25(1):262-266.

158. Hewett T, Myer G, Ford K. Decrease in neuromuscular control about the knee with maturation in female athletes. *J Bone Joint Surg Am.* 2004;86(8):1601-1608.

159. Hewett T, Myer G, Ford K, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. *Am J Sports Med.* 2005;33(4):492-501.

160. Hirokawa S, Solomonow M, Luo Z, Lu Y, D'Ambrosia R. Muscular co-contraction and control of knee stability. *J Electromyogr Kinesiol.* 1991;1(3):199-208.

161. Hogervorst T, Brand R. Joint mechanoreceptors and knee function. In: Pedowitz R, O'Connor J, Akeson W, eds. *Daniel's Knee Injuries. Ligament and Cartilage, Structure, Function, Injury, and Repair*. 2nd ed. Philadelphia: Lippincott Williams and Wilkins; 2003:127-148.

162. Holder-Powell H, Rutherford O. Unilateral lower limb injury: its long-term effects on quadriceps, hamstring, and plantarflexor muscle strength. *Arch Phys Med Rehabil.* 1999;80(6):717-720.

163. Holt B, Lambourne K. The impact of different warm-up protocols on vertical jump performance in male collegiate athletes. *J Strength Cond Res.* 2008;22(1):226-229.

164. Hootman JM, Dick R, Agel J. Epidemiology of collegiate injuries for 15 sports: summary and recommendations for injury prevention initiatives. *J Athl Train.* 2007;42(2):311-319.
165. Horak F, Nashner L. Central programming of postural movements: adaptation to altered support-surface configurations. *J Neurophysiol.* 1986;55(6):1369-1381.
166. Horita T, Komi P, Nicol C, Kyröläinen H. Stretch shortening cycle fatigue: interactions among joint stiffness, reflex, and muscle mechanical performance in the drop jump. *Eur J Appl Physiol.* 1996;73(5):393-403.
167. Hsieh H, Walker P. Stabilizing mechanisms of the loaded and unloaded knee joint. *J Bone Joint Surg Am.* 1976;58(1):87-93.
168. Hubley C, Wells R. A work-energy approach to determine individual joint contributions to vertical jump performance. *Euro J Appl Physiol Occup Physiol.* 1983;50(2):247-254.
169. Hunter J, Marshall R, McNair P. Relationships between ground reaction force impulse and kinematics of sprint-running acceleration. *J Appl Biomech.* 2005;21(1):31-43.
170. Hurd WJ, Axe MJ, Snyder-Mackler L. A 10-Year Prospective Trial of a Patient Management Algorithm and Screening Examination for Highly Active Individuals with ACL Injury. Part II: Determinants of Dynamic Knee Stability. *Am J Sports Med.* 2008;36(1):48-56.
171. Hurley M. Evaluation of reliability, reproducibility and validity of two methods of assessing proprioceptive acuity in the lower limb. *Br J Rheumatol.* 1996;35(1 suppl):140.
172. Hurley M. The effects of joint damage on muscle function, proprioception and rehabilitation. *Man Ther.* 1997;2(1):11-17.
173. Hurley M, Scott D, Rees J, Newham D. Sensorimotor changes and functional performance in patients with knee osteoarthritis. *Ann Rheum Dis.* 1997;56(11):641-648.
174. Huston L, Wojtys E. Neuromuscular performance characteristics in elite female athletes. *Am J Sports Med.* 1996;24(4):427-436.
175. Huston L, Wojtys E. The influence of the neuromuscular system on joint stability. In: Griffin L, ed. *Prevention of Noncontact ACL Injuries*. Rosemont, IL: American Academy of Orthopaedic Surgeons; 2001:53-61.
176. Ihara H, Nakayama A. Dynamic joint control training for knee ligament injuries. *Am J Sports Med.* 1986;14(4):309-315.
177. IHF. International Handball Federation: Member Organizations. Available at: http://www.ihf.info/TheIHF/MemberFederations/tabid/161/Default.aspx. Accessed 30 September, 2012.
178. Imran A, O'Connor J. Control of knee stability after ACL injury or repair: interaction between hamstrings contraction and tibial translation. *Clin Biomech.* 1998;13(3):153-162.
179. IRB. International Rugby Board - IRB Organization. Available at: http://www.irb.com/aboutirb/organisation/index.html. Accessed 22 September, 2012.
180. ISEK. Standards for Reporting EMG Data. *International Society of Electrophysiology and Kinesiology (ISEK)*. Available at: http://www.isek-online.org/standards_emg.html. Accessed 25 March, 2013.
181. James C, Sizer P, Starch D, Lockhart T, Slauterbeck J. Gender differences among saggital plane knee kinematic and ground reaction force characteristics during a rapid sprint and cut maneuver. *Res Q Exerc Sport.* 2004;75(1):31-38.
182. Johansson H. Role of knee ligaments in proprioception and regulation of muscle stiffness. *J Electromyogr Kinesiol.* 1991;1(3):158-179.

183. Johansson H, Pederson J, Bergenheim M, Djupsjöbacka M. Peripheral afferents of the knee: Their effects on central mechanisms regulating muscle stiffness, joint stability, and proprioception and coordination. In: Lephart S, Fu F, eds. *Proprioception and Neuromuscular Control in Joint Stability*. Illinois: Human Kinetics; 2000:5-22.

184. Johansson H, Sjölander P, Sojka P. Activity in receptor afferents from the anterior cruciate ligament evokes reflex effects on fusimotor neurones. *Neurosci Res.* 1990;8(1):54-59.

185. Johansson H, Sjölander P, Sojka P. A sensory role for the cruciate ligaments. *Clin Orthop Relat Res.* 1991(268):161-178.

186. Julian F, Morgan D. Variation of muscle stiffness with tension during tension transients and constant velocity shortening in the frog. *J Physiol.* 1981;319:193-203.

187. Julian F, Sollins M. Variation of muscle stiffness with force at increasing speeds of shortening. *J Gen Physiol.* 1975;66(3):287-302.

188. Juris P, Phillips E, Dalpe C, Edwards C, Gotlin R, Kane D. A dynamic test of lower extremity function following anterior cruciate ligament reconstruction and rehabilitation. *J Orthop Sp Phys Ther.* 1997;26(4):184-191.

189. Kadaba M, Ramakrishnan H, Wootten M. Measurement of lower extremity kinematics during level walking. *J Orthop Res.* 1990;8(3):383-392.

190. Kaneko F, Onari K, Kawaguchi K, Tsukisaka K, Roy SH. Electromechanical delay after ACL reconstruction: an innovative method for investigating central and peripheral contributions. *J Orthop Sp Phys Ther.* 2002;32(4):158-165.

191. Kannus P. Isokinetic evaluation of muscular performance: implications for muscle testing and rehabilitation. *Int J Sports Med.* 1994;15:S11-S18.

192. Kapandji IA. *The Physiology of the Joints: Lower Limb*. 5th ed: Churchill Livingstone; 1982.

193. Kaplan P, Walker C, Kilcoyne R, Brown D, Tusek D, Dussault R. Occult fracture patterns of the knee associated with anterior cruciate ligament tears: assessment with MR imaging. *Radiology.* 1992;183(3):835-838.

194. Katayama M, Higuchi H, Kimura M, et al. Proprioception and performance after anterior cruciate ligament rupture. *Int Orthop.* 2004;28(5):278-181.

195. Keays S, Bullock-Saxton J, Newcombe P, Keays A. The relationship between knee strength and functional stability before and after anterior cruciate ligament reconstruction. *J Orthop Res.* 2003;21(2):231-237.

196. Kennedy J, Alexander I, Hayes K. Nerve supply of the human knee and its functional importance. *Am J Sports Med.* 1982;10(6):329-335.

197. Kim A, Rosen A, Brander V, Buchanan T. Selective muscle activation following electrical stimulation of the collateral ligaments of the human knee joint. *Arch Phys Med Rehabil.* 1995;76(8):750-757.

198. KISTLER. KISTLER. Available at: http://www.kistler.com/us_en-us/KistlerCountryHome_KIC. Accessed July, 2012.

199. Knowles S, Marshall S, Miller T, et al. Cost of injuries from a prospective cohort study of North Carolina high school athletes. *Inj Prev.* 2007;13(6):416-421.

200. Knutson L, Soderberg G, Ballantyne B, Clarke W. A study of various normalization procedures for within day electromyographic data. *J Electromyogr Kinesiol.* 1994;4(1):47-59.

201. Kocher M, Steadman J, Briggs K, Sterett W, Hawkins R. Relationships between objective assessment of ligament stability and subjective assessment of symptoms and function after anterior cruciate ligament reconstruction. *Am J Sports Med.* 2004;32(3):629-634.

202. Koepsell T. Selecting a study design for injury research. In: Rivara E, Cummings P, Koepsell T, Grossman D, Maier R, eds. *Injury Control. A Guide to Research and Program Evaluation*. Cambridge: Cambridge University Press; 2001:89-103.

203. Koga H, Bahr R, Myklebust G, Engebretsen L, Grund T, Krosshaug T. Estimating anterior tibial translation from model-based image-matching of a noncontact anterior cruciate ligament injury in professional football: a case report. *Clin J Sport Med.* 2011;21(3):271-274.

204. Koga H, Nakamae A, Shima Y, et al. Mechanisms for noncontact anterior cruciate ligament injuries: knee joint kinematics in 10 injury situations from female team handball and basketball. *Am J Sports Med.* 2010;38(11):2218-2225.

205. Kostogiannis I, Ageberg E, Neuman P, Dahlberg L, Friden T, Roos H. Activity level and subjective knee function 15 years after anterior cruciate ligament injury: a prospective, longitudinal study of nonreconstructed patients. *Am J Sports Med.* 2007;35(7):1135-1143.

206. Kraemer WJ, Triplett NT, Fry AC, et al. An in-depth sports medicine profile of women college tennis players. *J Sport Rehabil.* 1995;4:79-98.

207. Kramer JF, Nusca D, Fowler P, Webster-Bogaert S. Test-retest reliability of the one-leg hop test following ACL reconstruction. *Clin J Sport Med.* 1992;2(4):240-243.

208. Krosshaug T, Nakamae A, Boden B, et al. Mechanisms of anterior cruciate ligament injury in basketball: video analysis of 39 cases. *Am J Sports Med.* 2007;35(3):359-367.

209. Krosshaug T, Slauterbeck J, Engebretsen L, Bahr R. Biomechanical analysis of anterior cruciate ligament injury mechanisms: three-dimensional motion reconstruction from video sequences. *Scand J Med Sci Sports.* 2007;17(5):508-519.

210. Kubo K, Kanehisa H, Fukunaga T. Effects of resistance and stretching training programmes on the viscoelastic properties of human tendon structures in vivo. *J Physiol.* 2002;538:219-226.

211. Kvist J, Ek A, Sporrstedt K, Good L. Fear of re-injury: a hindrance for returning to sports after anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc.* 2005;13(5):393-397.

212. Lambertz D, Goubel F, Pérot C. A method to evaluate reflex excitability of the human ankle plantarflexors despite changes in maximal activation capacities. *Exp Brain Res.* 2002;143(1):89-99.

213. LaStayo PC, Woolf JM, Lewek MD, Snyder-Mackler L, Reich T, Lindstedt SL. Eccentric muscle contractions: their contribution to injury, prevention, rehabilitation, and sport. *J Orthop Sports Phys Ther.* 2003;33(10):557-571.

214. Lederman E. *The Science and Practice of Manual Therapy*. 2nd ed: Churchill Livingstone; 2005.

215. Lee B, Kwon S, Kim J, Choi H, Min K. Comparison of clinical results according to amount of preserved remnant in arthroscopic anterior cruciate ligament reconstruction using quadrupled hamstring graft. *Arthroscopy.* 2008;24(5):560-568.

216. Lees A, Vanrenterghem J, De Clercq D. The maximal and submaximal vertical jump: implications for strength and conditioning. *J Strength Cond Res.* 2004;18(4):787-791.

217. Lephart S, Abt J, Ferris C, et al. Neuromuscular and biomechanical characteristic changes in high school athletes: a plyometric versus basic resistance program. *Br J Sports Med.* 2005;39(12):932-938.

218. Lephart S, Ferris C, Riemann B, Myers J, Fu F. Gender differences in strength and lower extremity kinematics during landing. *Clin Orthop Relat Res.* 2002(401):162-169.

219. Lephart S, Henry T. Functional rehabilitation for the upper and lower extremity. *Orthop Clin North Am.* 1995;26(3):579-592.

220. Lephart S, Henry T. The physiological basis for open and closed kinetic chain rehabilitation for the upper extremity. *J Sport Rehabil.* 1996;5:71-87.

221. Lephart S, Perrin D, Fu F, Gieck J, McCue F, Irrgang J. Relationship between selected physical characteristics and functional capacity in the anterior cruciate ligament-insufficient athlete. *J Orthop Sp Phys Ther.* 1992;16(4):174-181.

222. Lephart S, Perrin D, Minger K, Fu F, Gieck J. Sport-specific functional performance tests for the ACL insufficient athlete. *J Athl Train.* 1989;24(2):119.

223. Lephart S, Pincivero D, Giraldo J, Fu F. The role of proprioception in the management and rehabilitation of athletic injuries. *Am J Sports Med.* 1997;25(1):130-137.

224. Lephart S, Pincivero D, Rozzi S. Proprioception of the ankle and knee. *Sports Med.* 1998;25(3):149-155.

225. Lephart S, Riemann B. The role of mechanoreceptors in functional joint stability. In: Griffin L, ed. *Prevention of Noncontact ACL Injuries*. Rosemont, IL: American Academy of Orthopaedic Surgeons; 2001:45-52.

226. Lephart S, Riemann B, Fu F. Introduction to the sensorimotor system. In: Lephart S, Fu F, eds. *Proprioception and Neuromuscular Control in Joint Stability.* Illinois: Human Kinetics; 2000:xvii-xxiv.

227. Lephart SM, Perrin D, Fu F. Functional performance tests for the anterior cruciate ligament insufficient athlete. *J Athl Train.* 1991;26:44-50.

228. Lewit K. *Manipulative Therapy in Rehabilitation of the Locomotor System*. 3rd ed. Oxford: Butterworth Heinemann; 1999.

229. Lindstedt S, LaStayo P, Reich T. When active muscles lengthen: properties and consequences of eccentric contractions. *News Physiol Sci.* 2001;16:256-261.

230. Lloyd D, Buchanan T. Strategies of muscular support of varus and valgus isometric loads at the human knee. *J Biomech.* 2001;34(10):1257-1267.

231. Logerstedt D, Grindem H, Lynch A, et al. Single-legged hop tests as predictors of self-reported knee function after anterior cruciate ligament reconstruction: The Delaware-Oslo ACL Cohort Study. *Am J Sports Med.* 2012;40(10):2348-2356.

232. Logerstedt DS, Snyder-Mackler L, Ritter RC, Axe MJ. Knee pain and mobility impairments: meniscal and articular cartilage lesions. *J Orthop Sp Phys Ther.* 2010;40(6):A1-A35.

233. Logerstedt DS, Snyder-Mackler L, Ritter RC, Axe MJ, Godges JJ. Knee stability and movement coordination impairments: knee ligament sprain: Clinical practice guidelines linked to the International Classification of Functioning, Disability, and Health from the Orthopaedic Section of the American Physical Therapy Association. *J Orthop Sp Phys Ther.* 2010;40(4):A1-A37.

234. Lohmander L, Östenberg A, Englund M, Roos H. High prevalence of knee osteoarthritis, pain, and functional limitations in female soccer players twelve years after anterior cruciate ligament injury. *Arthritis Rheum.* 2004;50(1):3145-3152.

235. Louie J, Mote Jr C. Contribution of the musculature to rotatory laxity and torsional stiffness at the knee. *J Biomech.* 1987;20(3):281-300.

236. Lubowitz J, Bernardini B, Reid 3rd J. Current concepts review: comprehensive physical examination for instability of the knee. *Am J Sports Med.* 2008;36(3):577-594.

237. Luhtanen P, Komi R. Segmental contribution to forces in vertical jump. *Euro J Appl Physiol Occup Physiol.* 1978;38(3):181-188.

238. MacLean C, Taunton J, Clement D, Regan W, Stanish W. Eccentric kinetic chain exercise as a conservative means of functionally rehabilitating chronic isolated insufficiency of the posterior cruciate ligament. *Clin J Sport Med.* 1999;9(3):142-150.

239. MacWilliams B, Wilson D, DesJardins J, Romero J, Chao E. Hamstrings cocontraction reduces internal rotation, anterior translation, and anterior cruciate ligament load in weight-bearing flexion. *J Orthop Res.* 1999;17(6):817-822.

240. Madden M. *Relationship between knee active joint position sense and knee functional joint stability* [Master of Science Thesis]. London: Department of Physiology, University College London; 2005.

241. Magee D. *Orthopedic Physical Assessment*. 5th ed. St Louis: Saunders; 2007.

242. Majewski M, Susanne H, Klaus S. Epidemiology of athletic knee injuries: A 10-year study. *Knee.* 2006;13(3):184-188.

243. Malinzak R, Colby S, Kirkendall D, Yu B, Garrett W. A comparison of knee joint motion patterns between men and women in selected athletic tasks. *Clin Biomech.* 2001;16(5):438-445.

244. Margheritini F, Rihn J, Musahl V, Mariani P, Harner C. Posterior cruciate ligament injuries in the athlete: an anatomical, biomechanical and clinical review. *Sports Med* 2002;32(6):393-408.

245. Markolf K, Burchfield D, Shapiro M, Shepard M, Finerman G, Slauterbeck J. Combined knee loading states that generate high anterior cruciate ligament forces. *J Orthop Res.* 1995;13(6):930-935.

246. Markolf KL, Bargar WL, Shoemaker SC, Amstutz HC. The role of joint load in knee stability. *J Bone Joint Surg Am.* 1981;63(4):570-585.

247. Marshall S, Padua D, McGrath M. Incidence of ACL injury. In: Hewett T, Shultz S, Griffin L, eds. *Understanding and Preventing Noncontact ACL Injuries*. Illinois: Human Kinetics; 2007:5-29.

248. Martin J, Jessell T. Anatomy of the somatic sensory system. In: Kandel E, Schwartz J, Jessell T, eds. *Principles of Neural Science*. 3rd ed. London: Prentice-Hall International Inc.; 1991:353-366.

249. Martin J, Jessell T. Modality coding in the somatic sensory system. In: Kandel E, Schwartz J, Jessell T, eds. *Principles of Neural Science*. 3rd ed. London: Prentice-Hall International Inc.; 1991:341-352.

250. Mascarenhas R, Tranovich M, Kropf E, Fu F, Harner C. Bone-patellar tendon-bone autograft versus hamstring autograft anterior cruciate ligament reconstruction in the young athlete: a retrospective matched analysis with 2-10 year follow-up. *Knee Surg Sports Traumatol Arthrosc.* 2012;In press.

251. Matthews P. The human stretch reflex and the motor cortex. *Trends Neurosci.* 1991;14(3):87-91.

252. McNair P, Wood G, Marshall R. Stiffness of the hamstring muscles and its relationship to function in anterior cruciate ligament deficient individuals. *Clin Biomech.* 1992;7(3):131-137.

253. MEDmetric. KT1000. *MEDmetric Corporation*. Available at: http://www.medmetric.com/kt1.htm. Accessed July, 2012.

254. Merletti R. Standards for reporting EMG data. *J Electromyogr Kinesiol.* 1999;9(1):iii-iv.

255. Merton P. Voluntary strength and fatigue. *J Physiol.* 1954;123(3):553-564.

256. Meylan C, McMaster T, Cronin J, Mohammad N, Rogers C, Deklerk M. Single-leg lateral, horizontal, and vertical jump assessment: reliability, interrelationships, and ability to predict sprint and change-of-direction performance. *J Strength Cond Res.* 2009;23(4):1140-1147.

257. Mirbagheri M, Barbeau H, Kearney R. Intrinsic and reflex contributions to human ankle stiffness: variation with activation level and position. *Exp Brain Res.* 2000;135(4):423-436.

258. Mithoefer K, Hambly K, Logerstedt D, Ricci M, Silvers H, Della Villa S. Current concepts for rehabilitation and return to sport after knee articular cartilage repair in the athlete. *J Orthop Sp Phys Ther.* 2012;42(3):254-273.

259. Moksnes H, Risberg M. Performance-based functional evaluation of non-operative and operative treatment after anterior cruciate ligament injury. *Scand J Med Sci Sports.* 2009;19(3):345-355.

260. Moksnes H, Snyder-Mackler L, Risberg M. Individuals with an anterior cruciate ligament-deficient knee classified as noncopers may be candidates for nonsurgical rehabilitation. *J Orthop Sp Phys Ther.* 2008;38(10):586-595.

261. More R, Karras B, Neiman R, Fritschy D, Woo S, Daniel D. Hamstrings - an anterior cruciate ligament protagonist. An in vitro study. *Am J Sports Med.* 1993;21(2):231-237.

262. Morrissey M, Harman E, Johnson M. Resistance training modes: specificity and effectiveness. *Med Sci Sports Exerc.* 1995;27(5):648-660.

263. Morrissey M, Perry M, King J. Is knee laxity change after ACL injury and surgery related to open kinetic chain knee extensor training load? *Am J Phys Med Rehabil.* 2009;88(5):369-375.

264. Mountcastle S, Posner M, Kragh Jr J, Taylor D. Gender differences in anterior cruciate ligament injury vary with activity: epidemiology of anterior cruciate ligament injuries in a young, athletic population. *Am J Sports Med.* 2007;35(10):1635-1642.

265. Muaidi Q, Nicholson L, Refshauge K. Proprioceptive acuity in active rotation movements in healthy knees. *Arch Phys Med Rehabil.* 2008;89(2):371-371.

266. Muaidi Q, Nicholson L, Refshauge K. Do elite athletes exhibit enhanced proprioceptive acuity, range and strength of knee rotation compared with non-athletes? *Scand J Med Sci Sports.* 2009;19(1):103-112.

267. Muaidi Q, Nicholson L, Refshauge K, Adams R, Roe J. Effect of anterior cruciate ligament injury and reconstruction on proprioceptive acuity of knee rotation in the transverse plane. *Am J Sports Med.* 2009;37(8):1618-1626.

268. Mueller M, Maluf K. Tissue adaptation to physical stress: a proposed "Physical Stress Theory" to guide physical therapist practice, education, and research. *Phys Ther.* 2002;82(4):383-403.

269. Munro A, Herrington L. Between-session reliability of four hop tests and the agility T-test. *J Strength Cond Res.* 2011;25(5):1470-1477.

270. Myklebust G, Maehlum S, Engebretsen L, Strand T, Solheim E. Registration of cruciate ligament injuries in Norwegian top level team handball. A prospective study covering two seasons. *Scand J Med Sci Sports.* 1997;7(5):289-292.

271. Nade S, Newbold P. Pressure-volume relationships and elastance in the knee joint of the dog. *J Physiol.* 1984;357:417-439.

272. Nagai T, Heebner N, Sell T, Nakagawa T, Fu F, Lephart S. Restoration of saggital and transverse plane proprioception following anatomic double-bundle ACL reconstruction. *Knee Surg Sports Traumatol Arthrosc.* 2012;In press.

273. Nagai T, Sell T, House A, Abt J, Lephart S. Knee proprioception and strength and landing kinematics during a single-leg stop-jump task. *J Athl Train.* 2012;48(1):31-38.

274. Nagai T, Sell TC, Abt JP, Lephart SM. Reliability, precision, and gender differences in knee internal/external rotation proprioception measurements. *Phys Ther Sp.* 2012;13(4):233-237.

275. Neumann D. *Kinesiology of the Musculoskeletal System*. Baltimore: Mosby; 2002.

276. NORAXON. NORAXON. Available at: http://www.noraxon.com/, 2013.

277. Noyes F, Barber S, Mangine R. Abnormal lower limb symmetry determined by function hop tests after anterior cruciate ligament rupture. *Am J Sports Med.* 1991;19(5):513-518.

278. Noyes F, Barber S, Mooar L. A rationale for assessing sports activity levels and limitations in knee disorders. *Clin Orthop Relat Res.* 1989(246):238-249.

279. Noyes F, Cummings J, Grood E, Walz-Hasselfeld K, Wroble R. The diagnosis of knee motion limits, subluxations, and ligament injury. *Am J Sports Med.* 1991;19(2):163-171.

280. Noyes F, Grood E, Butler D, Raterman L. Knee ligament tests: what do they really mean? *Phys Ther.* 1980;60(12):1578-1581.

281. Noyes F, Matthews D, Mooar P, Grood E. The symptomatic anterior cruciate-deficient knee. Part II: the results of rehabilitation, activity modification, and counseling on functional disability. *J Bone Joint Surg Am.* 1983;65(2):163-174.

282. Noyes F, Mooar P, Matthews D, Butler D. The symptomatic anterior cruciate-deficient knee. Part I: the long-term functional disability in athletically active individuals. *J Bone Joint Surg Am.* 1983;65(2):154-162.

283. Noyes F, Torvik P, Hyde W, DeLucas J. Biomechanics of ligament failure. II. An analysis of immobilization, exercise, and reconditioning effects in primates. *J Bone Joint Surg Am.* 1974;56(7):1406-1418.

284. Nyland J, Klein S, Caborn D. Lower extremity compensatory neuromuscular and biomechanical adaptations 2 to 11 years after anterior cruciate ligament reconstruction. *Arthroscopy.* 2010;26(9):1212-1225.

285. Olmstead T, Wevers H, Bryant J, Gouw G. Effect of muscular activity on valgus/varus laxity and stiffness of the knee. *J Biomech.* 1986;19(8):565-577.

286. Olsen O, Myklebust G, Engebretsen L, Bahr R. Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis. *Am J Sports Med.* 2004;32(4):1002-1012.

287. Olsen O, Myklebust G, Engebretsen L, Holme I, Bahr R. Exercises to prevent lower limb injuries in youth sports: cluster randomised controlled trial. *BMJ.* 2005;330(7489):449.

288. Padulo J, Tiloca A, Powell D, Granatelli G, Bianco A, Paoli A. EMG amplitude of the biceps femoris during jumping compared to landing movements. *SpringerPlus.* 2013;2(1):520.

289. Page P, Frank C, Lardner R. *Assessment and Treatment of Muscle Imbalance. The Janda Approach*. Illinois: Humnan Kinetics Publishers; 2010.

290. Palmieri-Smith R, Wojtys E, Ashton-Miller J. Association between preparatory muscle activation and peak valgus knee angle. *J Electromyogr Kinesiol.* 2008;18(6):973-979.

291. Panjabi M. The stabilizing system of the spine. Part I. Function, dysfunction, adaptation, and enhancement. *J Spinal Disord.* 1992;5(4):383-389.

292. Perlau R, Frank C, Fick G. The effect of elastic bandages on human knee proprioception in the uninjured population. *Am J Sports Med.* 1995;23(2):251-255.

293. Perrin D. *Isokinetic Exercise and Assessment*: Human Kinetics; 1993.

294. Petschnig R, Baron R, Albrecht M. The relationship between isokinetic quadriceps strength test and hop tests for distance and one-legged vertical jump test following anterior cruciate ligament reconstruction. *J Orthop Sp Phys Ther.* 1998;28(1):23-31.

295. Pincivero D, Lephart S, Karunakara R. Relation between open and closed kinematic chain assessment of knee strength and functional performance. *Clin J Sport Med.* 1997;7(1):11-16.

296. Pitman M, Nainzadeh N, Menche D, Gasalberti R, Song E. The intraoperative evaluation of the neurosensory function of the anterior cruciate ligament in humans using somatosensory evoked potentials. *Arthroscopy.* 1992;8(4):442-447.

297. Pope M, Johnson R, Brown D, Tighe C. The role of the musculature in injuries to the medial collateral ligament. *J Bone Joint Surg Am.* 1979;61(3):398-402.

298. Portney L, Watkins M. *Foundations of Clinical Research: Applications to Practice*. 3rd ed. New Jersey: Pearson/Prentice Hall; 2009.

299. Powers C. The influence of abnormal hip mechanics on knee injury: a biomechanical perspective. *J Orthop Sp Phys Ther.* 2010;40(2):42-51.

300. Proske U, Morgan DL, Gregory JE. Thixotropy in skeletal muscle and in muscle spindles: a review. *Prog Neurobiol.* 1993;41(6):705-721.

301. Rack P, Ross H, Thilmann A, Walters D. Reflex responses at the human ankle: the importance of tendon compliance. *J Physiol.* 1983;344:503-524.

302. Rakos D, Shaw K, Fedor R, Lamanna M, Yocum C, Lawrence K. Interrater reliability of the active-knee-extension test for hamstring length in school-aged children. *Pediatr Phys Ther.* 2001;13(1):37-41.

303. Rangger C, Daniel D, Stone M, Kaufman K. Diagnosis of an ACL disruption with KT-1000 arthrometer measurements. *Knee Surg Sports Traumatol Arthrosc.* 1993;1(1):60-66.

304. Reeves N, Maganaris C, Narici M. Effect of strength training on human patella tendon mechanical properties of older individuals. *J Physiol.* 2003;548:971-981.

305. Reid A, Birmingham T, Stratford P, Alcock G, Giffin J. Hop testing provides a reliable and valid outcome measure during rehabilitation after anterior cruciate ligament reconstruction. *Phys Ther.* 2007;87(3):337-349.

306. Reinke E, Spindler K, Lorring D, et al. Hop tests correlate with IKDC and KOOS at minimum of 2 years after primary ACL reconstruction. *Knee Surg Sports Traumatol Arthrosc.* 2011;19(11):1806-1816.

307. Renström P, Arms S, Stanwyck T, Johnson R, Pope M. Strain within the anterior cruciate ligament during hamstring and quadriceps activity. *Am J Sports Med.* 1986;14(1):83-87.

308. Riemann B, Lephart S. The sensorimotor system, part I: the physiologic basis of functional joint stability. *J Athl Train.* 2002;37:71-79.

309. Riemann BL, Lephart SM. The sensorimotor system, part II: the role of proprioception in motor control and functional joint stability. *J Athl Train.* 2002;37(1):80-84.

310. Riemann BL, Myers JB, Lephart SM. Sensorimotor system measurement techniques. *J Athl Train.* 2002;37(1):85-98.

311. Rihn J, Irrgang J, Chhabra A, Fu F, Harner C. Does irradiation affect the clinical outcome of patellar tendon allograft ACL reconstruction? *Knee Surg Sports Traumatol Arthrosc.* 2006;14(9):885-896.

312. Risberg M, Beynnon B, Peura G, Uh B. Proprioception after anterior cruciate ligament reconstruction with and without bracing. *Knee Surg Sports Traumatol Arthrosc.* 1999;7(5):303-309.

313. Risberg M, Holm I, Tjomsland O, Ljunggren E, Ekeland A. Prospective study of changes in impairments and disabilities after anterior cruciate ligament reconstruction. *J Orthop Sp Phys Ther.* 1999;29(7):400-412.

314. Rivara F. Introduction: the scientific basis for injury control. *Epidemiol Rev.* 2003;25:20-23.

315. Roberts D, Ageberg E, Andersson G, Fridén T. Clinical measurements of proprioception, muscle strength and laxity in relation to function in the ACL-injured knee. *Knee Surg Sports Traumatol Arthrosc.* 2007;15(1):9-16.

316. Rolls A, Georgeb K. The relationship between hamstring muscle injuries and hamstring muscle length in young elite footballers. *Phys Ther Sp.* 2004;5:179-187.

317. Roos E, Herzog W, Block J, Bennell K. Muscle weakness, afferent sensory dysfunction, and exercise in knee osteoarthritis. *Nat Rev Rheumatol.* 2011;7(1):57-63.

318. Ross MD. The relationship between functional levels and fear-avoidance beliefs following anterior cruciate ligament reconstruction. *J Orthop Traumatol.* 2010;11(4):237-243.

319. Rothwell J. *Control of Human Voluntary Movement*. 2nd ed. London: Chapman and Hall; 1994.

320. Rozzi S, Lephart S, Gear W, Fu F. Knee joint laxity and neuromuscular characteristics of male and female soccer and basketball players. *Am J Sports Med.* 1999;27(3):312-319.

321. Rozzi SL, Lephart SM, Fu FH. Effects of muscular fatigue on knee joint laxity and neuromuscular characteristics of male and female athletes. *J Athl Train.* 1999;34(2):106-114.

322. Rudolph K, Axe M, Snyder-Mackler L. Dynamic stability after ACL injury: who can hop? *Knee Surg Sports Traumatol Arthrosc.* 2000;8(5):262-269.

323. Russell K, Palmieri R, Zinder S, Ingersoll C. Sex differences in valgus knee angle during a single-leg drop jump. *J Athl Train.* 2006;41(2):166-171.

324. Rutherford O, Jones D, Newham D. Clinical and experimental application of the percutaneous twitch superimposition technique for the study of human muscle activation. *J Neurol Neurosurg Psychiatry.* 1986;49(11):1288-1291.

325. Safran M, Allen A, Lephart S, Borsa P, Fu F, Harner C. Proprioception in the posterior cruciate ligament deficient knee. *Knee Surg Sports Traumatol Arthrosc.* 1999;7(5):310-317.

326. Safran MR, Harner CD, Giraldo JL, Lephart SM, Borsa PA, Fu FH. Effects of injury and reconstruction of the posterior cruciate ligament on proprioception and neuromuscular control. *J Sport Rehabil.* 1999;8(304-321).

327. Sahaly R, Vandewalle H, Driss T, Monod H. Maximal voluntary force and rate of force development in humans - importance of instruction. *Eur J Appl Physiol.* 2001;85(3-4):345-350.

328. Sahrmann S. *Diagnosis and Treatment of Movement Impairment Syndromes*. St louis: Mosby; 2002.

329. Sanders T, Medynski M, Feller J, Lawhorn K. Bone contusion patterns of the knee at MR imaging: footprint of the mechanism of injury. *Radiographics.* 2000;20:S135-S151.

330. Santello M. Review of motor control mechanisms underlying impact absorption from falls. *Gait Posture.* 2005;21(1):85-94.

331. Santello M, McDonagh M. The control of timing and amplitude of EMG activity in landing movements in humans. *Exp Physiol.* 1998;83(6):857-874.

332. Santello M, McDonagh MJ, Challis JH. Visual and non-visual control of landing movements in humans. *J Physiol.* 2001;537:313-327.

333. Sapega A. Muscle performance evaluation in orthopaedic practice. *J Bone Joint Surg Am.* 1990;72(10):1562-1574.

334. Saper C, Iversen S, Frackowiak R. Integration of sensory and motor function: The association areas of the cerebral cortex and the cognitive capabilities of the brain. In: Kandel E, Schwartz J, Jessell T, eds. *Principles of neural science*. 4th ed. New York: McGraw-Hill; 2000:349-380.

335. Schutte M, Dabezies E, Zimny M, Happel L. Neural anatomy of the human anterior cruciate ligament. *J Bone Joint Surg Am.* 1987;69(2):243-247.

336. Sekiya I, Muneta T, Ogiuchi T, Yagishita K, Yamamoto H. Significance of the single-legged hop test to the anterior cruciate ligament-reconstructed knee in relation to muscle strength and anterior laxity. *Am J Sports Med.* 1998;26(3):384-388.

337. Sell T. *Neuromechanical Predictors of Dynamic Knee Stability* [PhD Dissertation]. Pittsburgh: Department of Sports Medicine and Nutrition, University of Pittsburgh; 2004.

338. Sell T. An examination, correlation, and comparison of static and dynamic measures of postural stability in healthy, physically active adult. *Phys Ther Sp.* 2011;13(2):80-86.

339. Sell T, Abt J, Crawford K, et al. Warrior model for human performance and injury prevention: Eagle Tactical Athlete Program (ETAP) Part I. *J Spec Oper Med.* 2010;10(4):2-21.

340. Sell T, Chu Y, Abt J, et al. Minimal additional weight of combat equipment alters air assault soldiers' landing biomechanics. *Mil Med.* 2010;175(1):41-47.

341. Sell T, Ferris C, Abt J, et al. The effect of direction and reaction on the neuromuscular and biomechanical characteristics of the knee during tasks that simulate the noncontact anterior cruciate ligament injury mechanism. *Am J Sports Med.* 2006;34(1):43-54.

342. Sell T, Ferris C, Abt J, et al. Predictors of proximal tibia anterior shear force during a vertical stop-jump. *J Orthop Res.* 2007;25(12):1589-1597.

343. SENIAM. The SENIAM Project (Surface Electromyography for the Non-Invasive Assessment of Muscles). *SENIAM Project*. Available at: http://www.seniam.org/. Accessed 25 March, 2013.

344. Sernert N, Kartus J, Köhler K, et al. Analysis of subjective, objective and functional examination tests after anterior cruciate ligament reconstruction. A follow-up of 527 patients. *Knee Surg Sports Traumatol Arthrosc.* 1999;7(3):160-165.

345. Seynnes O, Erskine R, Maganaris C, et al. Training-induced changes in structural and mechanical properties of the patellar tendon are related to muscle hypertrophy but not to strength gains. *J Appl Physiol.* 2009;107(2):523-530.

346. Shelbourne K, Davis T, Patel D. The natural history of acute, isolated, nonoperatively treated posterior cruciate ligament injuries. A prospective study. *Am J Sports Med.* 1999;27(3):276-283.

347. Shelbourne K, Muthukaruppan Y. Subjective results of nonoperatively treated, acute, isolated posterior cruciate ligament injuries. *Arthroscopy.* 2005;21(4):457-461.

348. Shin CS, Chaudhari AM, Andriacchi TP. The effect of isolated valgus moments on ACL strain during single-leg landing: A simulation study. *J Biomech.* 2009;42(3):280-285.

349. Shultz S, Perrin D. Using surface electromyography to assess sex differences in neuromuscular response characteristics. *J Athl Train.* 1999;34(2):165-176.

350. Shumway-Cook A, Woollacott M. *Motor Control. Theory and Practical Applications*. 2nd ed. Philadelphia: Lippincott, Williams & Wilkins; 2001.

351. Sigward S, Powers C. The influence of gender on knee kinematics, kinetics and muscle activation patterns during side-step cutting. *Clin Biomech.* 2006;21(1):41-48.

352. Simmons S, Lephart S, Rubash H, Borsa P, Barrack R. Proprioception following total knee arthroplasty with and without the posterior cruciate ligament. *J Arthroplasty.* 1996;11(7):763-768.

353. Sinkjaer T, Toft E, Andreassen S, Hornemann B. Muscle stiffness in human ankle dorsiflexors: intrinsic and reflex components. *J Neurophysiol.* 1988;60(3):1110-1121.

354. Smith A, Milliner E. Injured athletes and the risk of suicide. *J Athl Train.* 1994;29(4):337-341.

355. Smith A, Scott S, Wiese D. The psychological effects of sports injuries. Coping. *Sports Medicine.* 1990;9(6):352-369.

356. Smoliga J, Myers J, Redfern M, Lephart S. Reliability and precision of EMG in leg, torso, and arm muscles during running. *J Electromyogr Kinesiol.* 2010;20(1):e1-e9.

357. Soderberg G, Cook T. Electromyography in biomechanics. *Phys Ther.* 1984;64(12):1813-1820.

358. Soderberg G, Knutson L. A guide for use and interpretation of kinesiologic electromyographic data. *Phys Ther.* 2000;80(5):485-498.

359. Sojka P, Sjölander P, Johansson H, Djupsjöbacka M. Influence from stretch-sensitive receptors in the collateral ligaments of the knee joint on the gamma-muscle-spindle systems of flexor and extensor muscles. *Neurosci Res.* 1991;11(1):55-62.

360. Soligard T, Myklebust G, Steffen K, et al. Comprehensive warm-up programme to prevent injuries in young female footballers: cluster randomised controlled trial. *BMJ.* 2008;337:a2469.

361. Stillman B, McMeeken J. The role of weightbearing in the clinical assessment of knee joint position sense. *Aust J Physiother.* 2001;47(4):247-253.

362. Swanik C, Harner C, Lephart S, Driban J. Neurophysiology of the knee. In: Scott W, ed. *Surgery of the Knee*. 4th ed. New York: Churchill Livingstone; 2006:99-119.

363. Swanik C, Lephart S, Giannantonio F, Fu F. Reestablishing proprioception and neuromuscular control in the ACL-injured athlete. *J Sport Rehab.* 1997;6:182-206.

364. Swanik C, Lephart S, Giraldo J, Demont R, Fu F. Reactive muscle firing of anterior cruciate ligament-injured females during functional activities. *J Athl Train.* 1999;34(2):121-129.

365. Swanik C, Lephart S, Swanik K, Stone D, Fu F. Neuromuscular dynamic restraint in women with anterior cruciate ligament injuries. *Clin Orthop Relat Res.* 2004(425):189-199.

366. Swearingen J, Lawrence E, Stevens J, Jackson C, Waggy C, Davis D. Correlation of single leg vertical jump, single leg hop for distance, and single leg hop for time. *Phys Ther Sport.* 2011;12(4):194-198.

367. Taylor J, McCloskey D. Detection of slow movements imposed at the elbow during active flexion in man. *J Physiol.* 1992;457:503-513.

368. Teitz C. Video analysis of ACL injuries. In: Griffin L, ed. *Prevention of Noncontact ACL Injuries*. Rosemont: American Academy of Orthopaedic Surgeons; 2001:87-92.

369. Thompson H, McKinley P. Landing from a jump: the role of vision when landing from known and unknown heights. *Neuroreport.* 1995;6(3):581-584.

370. Torzilli P, Deng X, Warren R. The effect of joint-compressive load and quadriceps muscle force on knee motion in the intact and anterior cruciate ligament-sectioned knee. *Am J Sports Med.* 1994;22(1):105-112.

371. Toutoungi D, Lu T, Leardini A, Catani F, O'Connor J. Cruciate ligament forces in the human knee during rehabilitation exercises. *Clin Biomech.* 2000;15(3):176-187.

372. Trentacosta N, Vitale M, Ahmad C. The effects of timing of pediatric knee ligament surgery on short-term academic performance in school-aged athletes. *Am J Sports Med.* 2009;37(9):1684-1691.

373. Tsuda E, Okamura Y, Otsuka H, Komatsu T, Tokuya S. Direct evidence of the anterior cruciate ligament-hamstring reflex arc in humans. *Am J Sports Med.* 2001;29(1):83-87.

374. Türker K. Electromyography: some methodological problems and issues. *Phys Ther.* 1993;73(10):698-710.

375. Vairo G, Myers J, Sell T, Fu F, Harner C, Lephart S. Neuromuscular and biomechanical landing performance subsequent to ipsilateral semitendinosus and gracilis autograft anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc.* 2008;16(1):2-14.

376. Van Deursen R, Simoneau G. Foot and ankle sensory neuropathy, proprioception, and postural stability. *J Orthop Sports Phys Ther.* 1999;29(12):718-726.

377. VERTEC. VERTEC Jump Trainer. Available at: http://www.sportsimports.com/blog/about-sports-imports/vertec-jump-trainer. Accessed July, 2012.

378. Vicon. Plug-In Gait Manual. Oxford: Vicon; 2000.

379. Vicon. Plug-In Gait. Product Guide - Foundation Notes. 2.0 ed. Oxford: Vicon; 2010.

380. Vicon. Vicon Nexus. Available at: http://www.vicon.com/products/nexus.html. Accessed July, 2012.

381. Vincent W. *Statistics in Kinesiology*. Illinois: Human Kinetics; 1995.

382. Viskontas D, Giuffre B, Duggal N, Graham D, Parker D, Coolican M. Bone bruises associated with ACL rupture: correlation with injury mechanism. *Am J Sports Med.* 2008;36(5):927-933.

383. von Porat A, Roos E, Roos H. High prevalence of osteoarthritis 14 years after an anterior cruciate ligament tear in male soccer players: a study of radiographic and patient relevant outcomes. *Annals of the Rheumatic Diseases.* 2004;63:269-273.

384. Waddington G, Seward H, Wrigley T, Lacey N, Adams R. Comparing wobble board and jump-landing training effects on knee and ankle movement discrimination. *J Sci Med Sport.* 2000;3(4):449-459.

385. Walshe A, Wilson G, Murphy A. The validity and reliability of a test of lower body musculotendinous stiffness. *Eur J Appl Physiol.* 1996;73(3-4):332-339.

386. Wikipedia. Circuit training. Available at: http://en.wikipedia.org/wiki/Circuit_training. Accessed 01 February, 2013.

387. Wikipedia. CrossFit. Available at: http://en.wikipedia.org/wiki/CrossFit. Accessed 10 February, 2013.

388. Wilk K, Romaniello W, Soscia S, Arrigo C, Andrews J. The relationship between subjective knee scores, isokinetic testing, and functional testing in the ACL-reconstructed knee. *J Orthop Sp Phys Ther.* 1994;20(2):60-73.

389. Wilkinson D, Moore P. *Measuring Performance: A Guide to Field-Based Fitness Testing*. Leeds, UK: National Coaching Foundation; 1995.

390. Windolf M, Götzen N, Morlock M. Systematic accuracy and precision analysis of video motion capturing systems - exemplified on the Vicon-460 system. *J Biomech.* 2008;41(12):2776-2780.

391. Winter D. *Biomechanics of Motor Control and Human Movement*. 3rd ed. New Jersey: John Wiley and Sons; 2005.

392. Winter E, Brookes F. Electromechanical response times and muscle elasticity in men and women. *Euro J Appl Physiol Occup Physiol.* 1991;63(2):124-128.

393. Wojtys E, Ashton-Miller J, Huston L. A gender-related difference in the contribution of the knee musculature to saggital-plane shear stiffness in subjects with similar knee laxity. *J Bone Joint Surg Am.* 2002;84(1):10-16.

394. Wojtys E, Huston L. Neuromuscular performance in normal and anterior cruciate ligament-deficient lower extremities. *Am J Sports Med.* 1994;22(1):89-104.

395. Wojtys E, Huston L. Longitudinal effects of anterior cruciate ligament injury and patellar tendon autograft reconstruction on neuromuscular performance. *Am J Sports Med.* 2000;28(3):336-344.

396. Wojtys E, Huston L, Schock H, Boylan J, Ashton-Miller J. Gender differences in muscular protection of the knee in torsion in size-matched athletes. *J Bone Joint Surg Am.* 2003;85(5):782-789.

397. Wojtys E, Huston L, Taylor P, Bastian S. Neuromuscular adaptations in isokinetic, isotonic, and agility training programs. *Am J Sports Med.* 1996;24(2):187-192.

398. Woltring H. Smoothing and differentiation techniques applied to 3D data. In: Allard P, Stokes I, Blanchi J-P, eds. *Three-Dimensional Analysis of Human Movement*. Illinois: Human Kinetics; 1994:79-100.

399. Yang J, Winter D. Electromyographic amplitude normalization methods: improving their sensitivity as diagnostic tools in gait analysis. *Arch Phys Med Rehabil.* 1984;65(9):517-521.

400. Yu B, McClure S, Onate J, Guskiewicz K, Kirkendall D, Garrett W. Age and gender effects on lower extremity kinematics of youth soccer players in a stop-jump task. *Am J Sports Med.* 2005;33(9):1356-1364.

401. Zazulak B, Ponce P, Straub S, Medvecky M, Avedisian L, Hewett T. Gender comparison of hip muscle activity during single-leg landing. *J Orthop Sports Phys Ther.* 2005;35:292-299.

402. Zhang S, Bates B, Dufek J. Contributions of lower extremity joints to energy dissipation during landings. *Med Sci Sports Exerc*. 2000;32(4):812-819.