Muscle Architecture and Neuromechanical Contributions to Athletic Performance and Injury

A thesis submitted for the degree

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By

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Certificate of Authorship and Originality of Thesis

I, Judd Kalkhoven, declare that this thesis, is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the Faculty of Health at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise reference or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

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"When you want to gladden your heart, think of the good qualities of those around you."

– Marcus Aurelius

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Preface

This thesis was prepared to fulfil the criteria for Doctor of Philosophy and is in the format of a compilation of published or submitted manuscripts. It adheres to the guidelines set forth in "Procedures for Presentation and Submission of Theses for Higher Degrees – University of Technology, Sydney: Policies and Procedures of the University". The subject matter of the manuscripts presented in this thesis are closely related and form a cohesive and consistent research narrative.

To address the research questions, two review articles, five original research articles and an editorial have been prepared. This thesis begins with an *Introduction* which provides salient background information on the topic, and outlines the research problem and aims of each of the articles. Two *Literature Reviews (chapters 2 & 3)* present an extensive analysis of the optimal muscle-tendon structural and mechanical characteristics for athletes, and the implications of mechanical contributions to muscle injury for injury risk mitigation. These were separated to enable the distinction of the two topics in peer-reviewed formats. This is followed by s*tudy 1*, a conceptual model and detailed framework for stress-related, strain-related, and overuse athletic injury *(chapter 4)*. This study was developed utilising the core concepts presented in the two literature reviews. Conceptual frameworks hold considerable value for the organization of ideas and the facilitation of future research and causal inferences. Accordingly, this framework served to inform the remainder of the thesis, facilitating the investigation of specific research links.

The content of the applied research studies is presented in *Chapters 5-7* in a logical order to address the research questions and describe the research narrative. The details of individual methodology and results are outlined in each corresponding chapter. Specifically, *study 2 (chapter 5)* presents an examination of the relationship between lower-body myometric muscle stiffness and strength in professional rugby union and Australian footballers. *Study 3, (chapter 6)* examined muscle architecture (fascicle length, pennation angle, and muscle thickness) in relation to anthropometrics and muscle force production characteristics in professional rugby union and Australian Football players. *Study 4 (chapter 7)* investigated the relationship between measures of muscle architecture, muscle stiffness, and neuromechanical markers of athletic performance in junior level Australian Football players. Each of these chapters has been prepared in accordance with the formatting requirements for the journals to which they have been submitted, therefore may differ slightly from each other and the remainder of the thesis.

The applied research studies are followed by a conceptual exploration of the causal pathways between training load and injury *(chapter 8)*. This article utilises key concepts presented in the conceptual framework in *chapter 4* to facilitate this enquiry. This is followed by an *editorial (chapter 9)* which highlights the multifactorial nature of overuse athletic injury. The *General Discussion (chapter 10)* summarises the collective outcomes of the thesis, and outlines how these outcomes contribute to the current body of literature. Finally, general conclusions are made and suggestions for future research are given.

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Abstract

This thesis examines muscle architecture and neuromechanical contributions to athletic performance and injury. To do this, two *Literature Reviews (chapters 2 & 3)* present an extensive analysis of the optimal muscle-tendon structural and mechanical characteristics for athletes, and the implications of mechanical contributions to muscle injury for injury risk mitigation. S*tudy 1* provided a conceptual model and detailed framework for stress-related, strain-related, and overuse athletic injury *(chapter 4)*. This article is focused on the concepts of tissue strength, stress and strain, and outlines the interplay between physiology and tissue mechanical properties. Furthermore, this article considers the importance of loading pattern, the non-linear relationship between cumulative load and cumulative damage, and the capacity of muscles to readily alter mechanical properties. This framework will guide injury research towards a more thorough investigation of causal mechanisms and understanding of risk factors. *Study 2 (chapter 5)* presents an examination of the relationship between lower-body myometric muscle stiffness and strength in professional rugby union and Australian footballers. The participants (n=64) were assessed for individual unilateral muscle stiffness of the rectus femoris (RF) and biceps femoris long head (BFlh) with torque and rate of torque development assessed for knee extension and flexion using isokinetic dynamometry. *Small* positive correlations between RF stiffness and leg extension torque and rate of torque development were exhibited. BFlh stiffness was not related to torque characteristics. When examined by code, rugby union players exhibited superior RF stiffness and leg extension torque production characteristics ($p < 0.05$) compared to the Australian Football group. There were minimal differences in BFlh stiffness and hamstring torque characteristics between codes. Higher myometric muscle stiffness was associated with heightened force

production characteristics in the quadriceps and this method of assessment may be beneficial for practitioners working with athletes that are required to perform dynamic activities. *Study 3 (chapter 6)* examined muscle architecture (fascicle length, pennation angle, and muscle thickness) in relation to anthropometrics and muscle force production characteristics in professional rugby union and Australian Football players. The participants (n=64) were assessed for unilateral muscle architecture measures (muscle thickness, pennation angle, and fascicle length) of the biceps femoris long head (BFlh) and vastus lateralis (VL) with isokinetic torque and rate of torque development assessed for knee extension and flexion. This study demonstrated that fascicle length, muscle thickness, pennation angle and stature are inter-related. It was also clear that there were relationships between muscle force production, muscle size and pennation angle normalised for muscle size. The findings from this study indicate that muscle architecture is related to both stature and force production characteristics in professional athletes and also highlight the need for appropriate data normalisation processes when relating these measures to athletic performance capabilities and injury outcomes. When comparing between the sporting codes of rugby union and Australian Football there were no signficant differences in the biceps femoris muscle architecture or hamstring force outputs. However, differences in all muscle architecture variables of the vastus lateralis muscle and quadriceps strength characteristics were evident between professional rugby union and Australian Rules football players. *Study 4 (chapter 7)* investigated the relationship between measures of muscle architecture, muscle stiffness, and neuromechanical markers of athletic performance in junior level Australian Football players. This study investigated the relationship between muscle architecture, myometric muscle stiffness and athletic performance markers in 16 elite-junior male Australian Football players. The participants were assessed for individual unilateral muscle stiffness of the rectus femoris (RF), biceps femoris long head (BFlh) and gastrocnemius muscles, unilateral muscle architecture measures (muscle thickness, pennation angle, and fascicle length) of the biceps femoris long head (BFlh) and vastus lateralis (VL), vertical stiffness (Kvert), torque and rate of torque development assessed for knee extension and flexion using isokinetic dynamometry, isometric squat and deadlift, and vertical jump ability. This study demonstrated that muscle stiffness was positively related to muscle force production characteristics in high-level developmental Australian footballers, with BF stiffness positively related to peak squat force and RFD. Furthermore, myometric muscle stiffness of the BF was positively related to CMJ jump height and DJ RSI. Interestingly, there were minimal relationships evident between measures of muscle architecture and strength characteristics, with the exception of a negative relationship between BF fascicle length and peak deadlift force, while BF muscle thickness and fascicle length were positively related to SJ RFD. A small number of muscle architecture and stiffness measures are related to force production characteristics and jumping ability in elite junior Australian footballers however with the predominance of *trivial* and *small* non-significant relationships evident, it is likely that a number of confounding factors affect these relationships. Accordingly, in light of previous research indicating the contributions of muscle architecture to muscle functioning in isolated settings, it appears that a more rigorous research approach accounting for potential confounders and utilising a greater sample size may be needed to better illuminate potential relationships between muscle architecture, mechanical stiffness and athletic performance competencies. *Study 5 (chapter 8)* utilised the conceptual framework presented in *study 1 (chapter 4)* to provide a conceptual exploration of the causal pathways between training load and injury. Here, the relation between specific training load measures and metrics, and causal pathways of gradual onset and traumatic injury were examined. In light of the notable shortcomings of currently available training load metrics and data when considering causal pathways to injury, as explored within *study 5a*, it was concluded that the utilisation of currently available training load metrics and data for injury risk assessment and manipulation should be avoided. In summary, this thesis proposed the utilisation of conceptual frameworks for facilitating research into athletic injury and performance. This resulted in the investigation of relevant research links within 3 data-based research studies, as well as a conceptual exploration into the causal pathways between training load and injury.

List of Definitions

Stress

Stress is defined as force per unit area and develops within a structure/tissue in response to externally applied mechanical loads (force). Stress is descriptive of the internal forces neighbouring particles of a given material exert on each other. Stress may be characterised as normal (force perpendicular to a plane) or shear (force parallel to a plane). Normal stress may be tensile or compressive depending on the mode of loading.

Strain

Refers to the amount of deformation expressed as a normalized change in shape or size. Two basic types of strain exist: normal strain, which is related to change in length, and shear strain, which is related to change in angle. Normal strain is the ratio of deformation (lengthening or shortening) to original length and as such may be tensile or compressive. Shear strain is the amount of angular deformation that occurs in a structure. For example, a rectangle drawn on one face of a solid before a shear stress is applied will appear as a parallelogram during the application of a shear stress

Mechanical load

Refers to the forces experienced by a specific tissue or biological structure and can be externally or internally sourced e.g., collision with an opponent or muscle pulling on bone. The mechanical load is the stimulus that results in the mechanical load-response (stress and strain).

Stiffness

Stiffness effectively describes the relationship between a given force and the deformation of an object or body and particularly refers to the property of a system to resist an applied stretch. The terms 'compliance' or 'compliancy' are commonly used interchangeably with stiffness and refer to the tendency of a system to yield to applied forces.

Young's Modulus

is defined as the ratio of stress to strain

Hooke's Law

a law stating that the strain in a solid is proportional to the applied stress within the elastic limit of that solid.

Elasticity

is related to the concept of stiffness and has commonly been defined as the ability of an object or material to resume its normal shape after being stretched or compressed.

Myometry

A technique for assessing the mechanical characteristics of various tissues, such as muscle tension, elasticity and stiffness. This technique involves a non-invasive palpation being applied to the skin immediately superior to the tissue being assessed.

Stretch-Shorten Cycle

The SSC is a phenomenon that occurs when musculotendinous tissue is stretched to cause eccentric tension immediately before concentric contraction. An effective SSC requires three critical elements. A well timed preactivation of the muscle prior to the eccentric phase, a short and fast eccentric phase, and an immediate transition (short delay) between stretch (eccentric) and shortening (concentric phase)

Hill Model of the musculotendinous unit

A commonly utilised 3-element model of the muscle-tendon complex. Consists of the contractile component/element (CE), series elastic component (SEC), and the parallel elastic component (PEC)

Muscle architecture

Muscle architecture refers to the physical arrangement of muscle fibers at the macroscopic level

Muscle damage

defined as a disruption to myofibrils within a muscle fiber, whereby the architecture of the sarcomeres becomes disorganized

Muscle strain injury

defined as a rupture of individual muscle fibers that can extend across a portion of fibers within a particular muscle (partial tear) or across the whole muscle (complete tear)

Training load

Training load is the term used by sports scientists, trainers, and athletes as the input variable that is manipulated to elicit a desired training response in athletes. Within this context, *load* is a generic term which is qualified by the term *training* in a fashion similar to other areas of research that have adopted the term *load* within a variety of contexts (i.e. allostatic load, cognitive load, mechanical load etc.). Accordingly, *training load* does not specifically refer to the forces experienced, as is typical in physics, or any other physical quantity. Training load, as a generic construct, accommodates a variety of proxy measures and metrics (spatio-temporal, mechanical, psycho-physiological etc.) which can be described as being external or internal depending on whether the measurable aspect in question is internal or external to the athlete. See below for explanations of terms *external* and *internal*.

External (training) load

In the context of training load, the term *external load* implicitly refers to the *external training load* undertaken by an athlete. External load has been defined as the physical work prescribed in the training plan (physical performance output). Notably, this does not refer to 'work' in the physics sense (force x distance) but more so in a generic manner. Accordingly, the term e*xternal load* accommodates quantification and prescription in variety of manners, enabling the use of a diverse range of *external load* measures and metrics. Some common measures of *external load* include GPS derived units (speed, accelerations, etc.) and level of resistance.

Internal (training) load

As per external load, the term internal load implicitly refers to internal training loads. In the context of training load, internal load typically refers to the psycho-physiological stress experienced by an athlete. Notably, in this context internal load does not describe the forces or internal stresses and strains experienced by biological tissues inside the body. Rather, internal load typically reflects the psycho-physiological response that an athlete initiates to cope with the requirements elicited by the external load, irrespective of how the external load is quantified. Therefore, the concept of internal load incorporates all the psycho-physiological responses initiated to cope with the requirements elicited by the external load, i.e., the execution of the exercise (single or sequence) according to the modalities prescribed by the coach.

Psycho-physiological load

Refers to the psycho-physiological stress experienced by an athlete in response to a given external load. A range of physiological and psychophysiological measures and metrics exist with common physiological measures being heart rate, blood lactate etc. and a common psychophysiological measure being rating of perceived exertion (RPE). The psycho-physiological stress experienced is considered to contribute substantially to the training outcome that presents. Notably, the value and validity of specific training load indicators depends on the context. For example, heart rate is a valid measure of internal load for endurance training but not so much for resistance training.

List of Abbreviations

ACSA	anatomical cross-sectional area
AF	Australian Football
AFL	Australian Football League
BFlh	biceps femoris long head
CE	contractile element
CSA	cross-sectional area
EFOV	extended field of view
EMD	electromechanical delay
Kleg	leg stiffness
Kvert	vertical stiffness
MSBF	Myometric stiffness biceps femoris
MSVL	Myometric stiffness vastus lateralis
MT	muscle thickness
MTU	muscle-tendon unit
PA	pennation angle
PCSA	physiological cross-sectional area
PEC	parallel elastic component
RF	rectus femoris
RFD	rate of force development
RTD	rate of torque development
RU	rugby union
SEC	series elastic component

SSC	stretch-shorten cycle
VL	vastus lateralis